VOYA

Great Lakes Area Resource Studies Unit

Michigan Technological University
Technical Report Series

PHYSICAL AND CHEMICAL FACTORS AFFECTING PRIMARY PRODUCTION IN THE VOYAGEURS NATIONAL PARK LAKE SYSTEM

Final Report

(GLARSU Tech. Rept. #29)

R. Kepner

and

R. Stottlemyer

Great Lakes Area Resource Studies Unit
Department of Biological Sciences
Michigan Technological University
Houghton, MI 49931

January 1988

This study was funded by the National Park Service under contract number CA-6820-5-8029.

Digitized by the Internet Archive
in 2012 with funding from
LYRASIS Members and Sloan Foundation

http://archive.org/details/physicalchemical00kepn

TABLE OF CONTENTS

LIST OF TABLES -- iii

LIST OF FIGURES --------------------------------------- iv

ABSTRACT -- vii

INTRODUCTION -- 1

SITE DESCRIPTION -------------------------------------- 3

Geology --- 4

Soils --- 4

Climate --- 6

METHODS --- 9

Quality Control --------------------------------------- 12

RESULTS AND DISCUSSION -------------------------------- 13

Physical Characteristics ------------------------------ 13

Lake Morphometry -------------------------------------- 13

Water Temperature ------------------------------------- 15

Dissolved Oxygen -------------------------------------- 18

Light Extinction -------------------------------------- 19

Chemical Characteristics ------------------------------ 21

Seasonal Inputs --------------------------------------- 21

Calcium --- 24

Magnesium --- 25

Sodium and Potassium ---------------------------------- 27

Ammonium -- 30

Sum of Cations -- 30

pH -- 32

Specific Conductance ---------------------------------- 34

Alkalinity 34

Nitrate 37

Total Kjeldahl Nitrogen 39

Phosphate 41

Total Phosphorus 41

Sulfate 42

Chloride 43

Chemical Relationships Among Lakes 46

Biological Characteristics 49

Chlorophyll-*a* 49

Trophic State Indices 52

Total Organic Carbon 54

Carbon Assimilation 57

Species Composition 64

SUMMARY 66

LITERATURE CITED 71

APPENDICES 81

LIST OF TABLES

Table Page

1. Primary open-water sampling stations and their locations by latitude and longitude ---------- 9
2. Morphometric parameters of the four study lakes ----- 13
3. Depths of thermal stratification observed at the eight main sampling stations ------------------ 16
4. Mean monthly vertical light extinction coefficients observed at the eight main sampling stations during 1985 --------------------- 19
5. Mean monthly volume-weighted ion concentrations for precipitation, runoff and lake water throughout the study ------------------------------ 22
6. Means and confidence limits for pH, alkalinity, and specific conductance values obtained at the eight main sampling stations ------------------- 33
7. Means and standard deviations of major ionic concentrations, sum of cations, pH and specific conductance for the eight main sampling stations throughout the study --------------------- 44
8. Mean summer chlorophyll-a concentrations of the four lakes in this and a previous study ------------ 51
9. Mean monthly trophic state indices for each of the four study lakes as obtained in this and a previous study ------------------------------------ 53
10. Mean total organic carbon concentrations and total organic carbon to total kjeldahl nitrogen ratios for each of the four study lakes and combined grab-sample sites ------------------------ 56
11. Mean net areal primary production estimates from this and 12 previous studies ------------------ 61
12. List of observed algal genera at the eight main sampling stations in August, 1985 and at the two Kabetogama Lake stations in October, 1985 ---------- 65
13. Comparison of ion concentrations for surface water (1 m) samples collected in October in east-Rainy Lake during the present study and by EPA (1986) ----- 66
14. Ranked mean values for pH, alkalinity, conductance, chl-a and carbon-assimilation rates for the four study lakes over the entire study ----------------- 67

LIST OF FIGURES

Figure — Page

1. Voyageurs National Park (VOYA) lake system -------- 2
2. 1985 and 1986 mean weekly lake levels for Namakan Reservoir and Rainy Lake ----------------- 3
3. Generalized geological map of VOYA --------------- 5
4. 1985 and 1986 mean monthly air temperature and precipitation amounts at International Falls, MN, compared to long-term averages ---------------- 7
5. Mean monthly precipitation amounts and stream discharge from Indian Creek ---------------------- 8
6. Drawdown curves for Namakan, Sand Point and Kabetogama Lakes ---------------------------------- 14
7. Mean monthly water column temperatures for the 8 main sampling stations ------------------------- 16
8. Mean monthly precipitation, stream, and lake sulfate concentrations during 1985 and 1986 ------ 23
9. Mean monthly precipitation, stream, and lake calcium concentrations during 1985 and 1986 ------ 23
10. Mean monthly calcium concentrations for the 8 main sampling stations ------------------------- 25
11. Mean monthly magnesium concentrations for the 8 main sampling stations ------------------------- 26
12. Mean monthly sodium concentrations for the 8 main sampling stations ------------------------- 28
13. Mean monthly potassium concentrations for the 8 main sampling stations ------------------------- 29
14. Mean monthly sum of cation concentrations for the 8 main sampling stations ------------------- 31
15. Relation between specific conductance and total cation concentration ----------------------------- 31
16. Mean monthly pH values for the 8 main sampling stations -------------------------------- 33
17. Mean specific conductance values for the 8 main sampling stations ------------------------- 35

18. Relation between specific conductance and bicarbonate alkalinity for 4 VOYA lakes ---------- 36

19. Mean monthly bicarbonate alkalinities for the 8 main sampling stations ------------------------ 36

20. Mean monthly nitrate concentrations for the 8 main sampling stations ------------------------ 38

21. Total kjeldahl nitrogen concentrations at 1 m for the 8 main sampling stations and 4 grab-sample sites during 1986 ------------------------ 40

22. Mean monthly sulfate concentrations for the 8 main sampling stations ------------------------ 43

23. Mean monthly chloride concentrations for the 8 main sampling stations ------------------------ 45

24. Relation between bicarbonate and calcium plus magnesium concentrations by lake station --------- 47

25. Relation between bicarbonate plus sulfate and calcium plus magnesium concentrations by lake station --- 47

26. Relation between bicarbonate to sulfate ratios and bicarbonate concentrations by lake station ----------------------------------- 48

27. Relation between calcium to magnesium ratios and bicarbonate concentrations by lake station ---------------------------------- 48

28. Relation between mean monthly bicarbonate and pH values for 8 main sampling stations ----------- 49

29. Mean monthly chlorophyll-a concentrations for the 8 main sampling stations -------------------- 50

30. Relation between mean pH and chlorophyll-a concentrations for 8 main stations by month ------- 52

31. Total organic carbon at 1 m for the 8 main sampling stations and 4 grab-sample sites during 1986 -- 55

32. Total organic carbon to total kjeldahl nitrogen ratios at station KB during 1986 ---------------- 56

33. Distribution by depth of mean volumetric carbon-assimilation rates for the 8 main sampling stations during 1985 and 1986 ------------------- 58

34. Mean monthly volumetric carbon-assimilation rates for the 8 main sampling stations ----------- 59

35. Mean monthly volumetric carbon-assimilation rates and standard deviations comparing Kabetogama to other 3 VOYA study lakes ----------- 60

36. Mean monthly integrated areal productivities for the 8 main sampling stations ----------------- 62

37. Relation between mean pH and mean volumetric carbon-assimilation rates for the 4 VOYA study lakes -- 63

38. Kabetogama Lake and watershed map ---------------- G-2

39. Comparison of model-generated TP concentrations under 1986 drawdown regime and under constant-volume (mean annual) conditions ------------------ G-6

40. Comparison of model-generated TP concentrations under 1986 drawdown regime and under projected "natural" lake level conditions ------------------ G-6

41. Comparison of model-generated TP concentrations under 1986 loadings and under zero in-basin population conditions ------------------------------ G-8

42. Comparison of model-generated TP concentrations under 1986 loadings and under a three-fold increase in in-basin population conditions -------- G-8

ABSTRACT

This final report comprises the results of a two-year study of water quality and phytoplankton productivity on selected larger lakes in Voyageurs National Park (VOYA), Minnesota. The objectives were to (1) acquire baseline data to establish a benchmark against which future change can be assessed in nutrient chemistry, biomass, and primary productivity; (2) to collect and analyze sufficient physical, chemical and biological data to validate and quantify differences in lake trophic states; and (3) to employ a simple mass-balance nutrient model to investigate possible mechanisms by which water level modification may influence lake productivity.

INTRODUCTION

Voyageurs National Park was established in 1975 to preserve a portion of the Superior-Quetico natural environment in accordance with its Organic Act (16 U.S.C. 1). As such, management should be restricted to practices that protect against, remove, or compensate for human actions that cause ecosystem departure from natural conditions. One objective for park management is to provide the National Park Service (NPS) with a rational basis upon which to determine if effects due to current water-level regulation are having adverse impacts on the park's aquatic biota. Impacts which do not promote the restoration of "natural conditions" (ie., do not comply with the Organic Act) are contradictory with park goals and mandate as formulated in the park's enabling legislation (Public Law 91-661, January 8, 1971).

Several studies have been conducted to assess the impact of fluctuating water levels on the park's aquatic life. Along with the study considered here, a hydrologic modeling analysis of lake level fluctuations (Flug 1986); the effects of lake level fluctuation on diversity, distribution and reproductive success of marsh and shoreline nesting birds, benthic macroinvertebrates, fish communities, beaver, otter, and muskrat populations; and studies on the combined effects on several of these organisms (Kallemeyn, et al. 1987) will all provide complementary data essential for informed management decisions concerning the park's aquatic resources.

Used for comparative purposes was the 1978-81 contract study of plankton communities in many of the park lakes. Directed by Dr. J.R. Hargis, then at the University of Minnesota-Duluth; physical, chemical and biological features (including chlorophyll-a, zooplankton densities, species compositions and diversities) were noted for the four lakes considered in this study. Baseline information was gathered over three summer periods. Similarities and differences between lakes were then used to suggest management categories for the park lakes (Hargis 1981). Discrepancies have been found in the Hargis data set, with some of the results being in definite error (Larry Kallemeyn, Voyageurs National Park, pers. comm.). Yet, there are no indications of systematic error which would cause us to reject all of the Hargis data. In conjunction with water chemistry monitoring at eleven sites by the Department of the Interior's Geological Survey (Payne 1978) and sixteen benchmark stations established by the Minnesota Pollution Control Agency (Anderl 1976), the Hargis study, despite its limitations, provides comparative data for the current project findings.

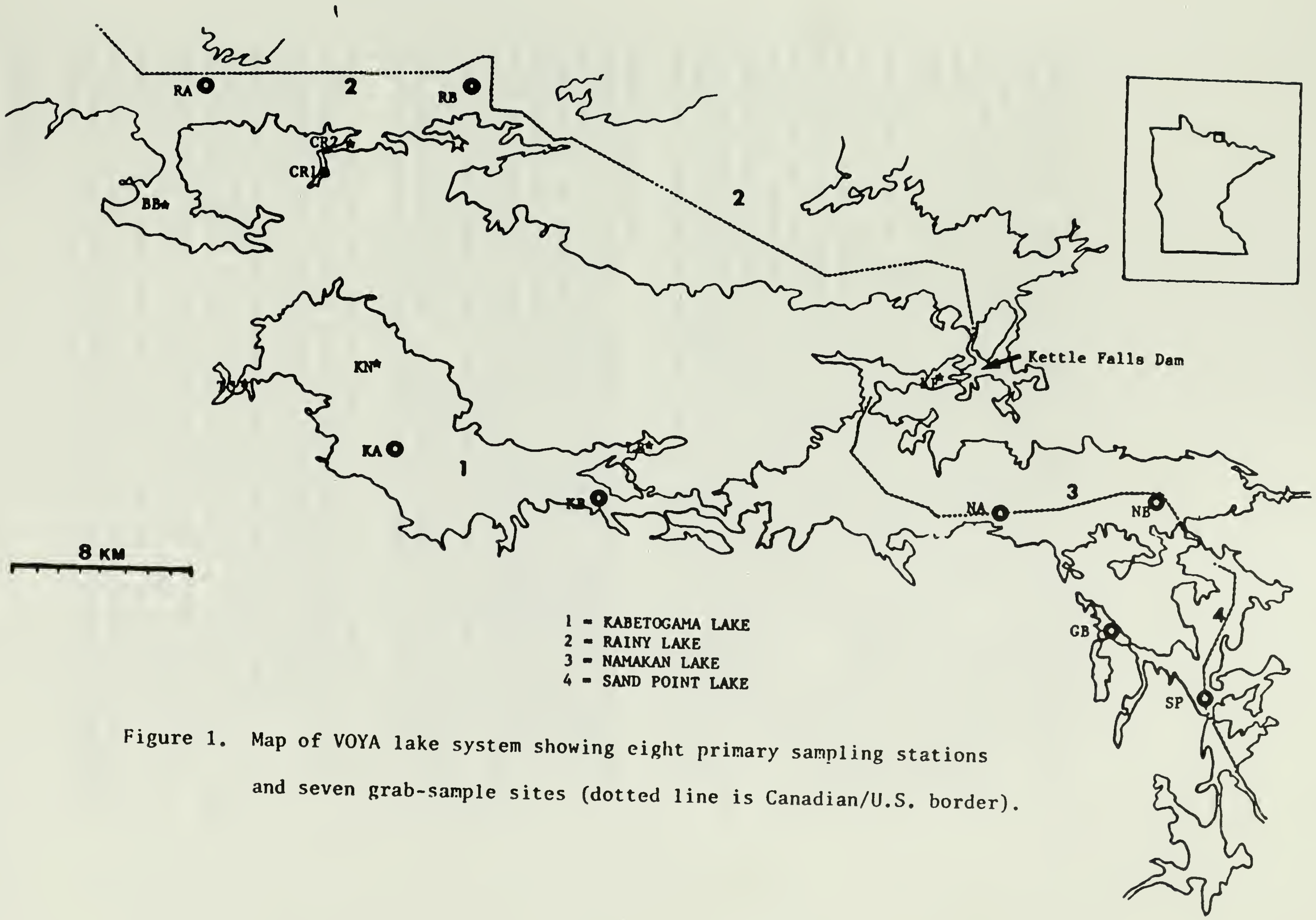


Figure 1. Map of VOYA lake system showing eight primary sampling stations and seven grab-sample sites (dotted line is Canadian/U.S. border).

SITE DESCRIPTION

The Voyageurs National Park (VOYA) lake system is located in the Boundary Waters area of north-central Minnesota (Fig. 1). To the north and east the park borders Ontario, Canada, and is bordered on the south and west by Kabetogama State Forest (2,830 km^2) and Superior National Forest (12,180 km^2). Approximately 40% of the 890 km^2 park area consists of the four large lakes considered in the present study. All of Kabetogama Lake and portions of Namakan, Sand Point, and Rainy Lakes lie within VOYA boundaries.

Water levels in the larger VOYA lakes are controlled by man. Rainy Lake level has been regulated since 1909 by a dam at its outlet, and levels of the other three lakes have been regulated since the 1912 construction of two smaller dams located between Namakan and Rainy Lakes. Lake levels are controlled according to general regulations established by the International Joint Commission (IJC). At present, the average annual water level fluctuation in Namakan Reservoir (ie. Kabetogama, Namakan, Sand Point and Crane Lakes) is approximately 2.7 meters (Fig. 2). The Corps of Engineers has projected that levels would fluctuate by roughly 1.9 m without the dams. Natural fluctuation would also differ in timing from present changes by (1) peaking in late May or early June instead of late June or early July, (2) generally declining instead of remaining stable over summer and fall, and (3) falling by approximately 0.6 m instead of 1.8 m over winter periods (Kallemeyn 1985, Flug 1986). Also lake levels and discharges would be more variable compared to the regulated system. The timing and magnitude of present water level regulation essentially imposes the equivalent of flood and drought conditions upon the Namakan Reservoir.

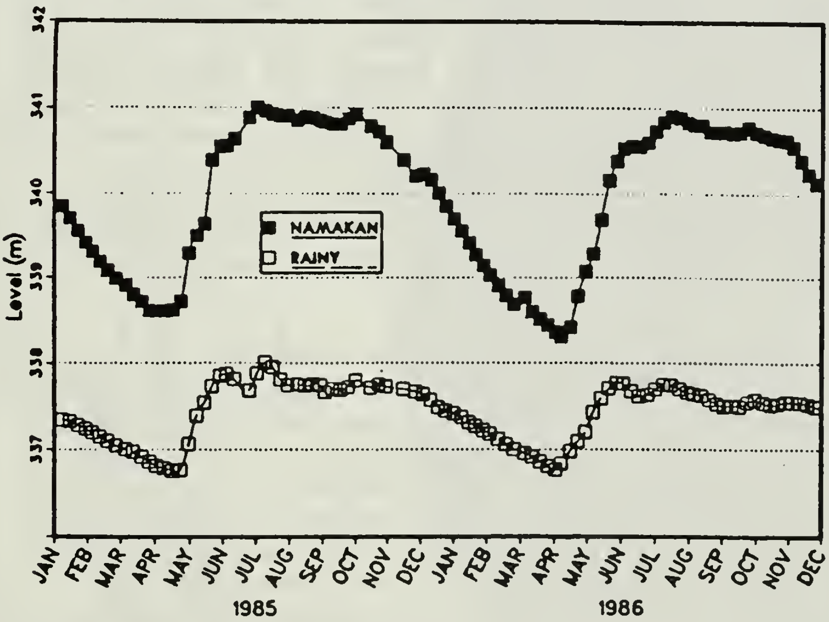


Figure 2. Mean weekly lake levels (m above sea level) for Namakan Reservoir (Kettle Falls Dam) and Rainy Lake (Fort Frances), during 1985 and 1986).

Geology

Located within the southern reaches of the Canadian Shield, the Voyageurs lake system is surrounded and underlain by the most extensive Precambrian geologic features in the nation (NPS 1973). The geological history of the region has been well-studied (Zumberge 1952; Goldich, et al. 1961; Schwartz and Thiel 1963; Minnesota Geological Survey 1969; Ojakangas and Southwick 1969; Ojakangas 1970, 1972; NPS 1973; Southwick and Ojakangas 1979; Ojakangas and Matsch 1982). Granite, biotite schist, and migmatite underlie most of the park except for the northwest corner of Rainy Lake where a major greenstone belt projects in from Ontario. More granite (the northern edge of the Vermillion Batholith) is found in the southern part of the park, while biotite schist is prevalent in the north (Fig. 3). All bedrock is Early Precambrian, roughly 2700 million years old (Ojakangas and Matsch 1982).

The surface morphology of the park has been modified by Pleistocene glaciation. The last of the glaciers retreated following the Wisconsin glaciation (50,000 to 10,000 B.P.), leaving behind the erratic terrain of the Kabetogama peninsula. Glacial scouring produced alternating rocky ridges divided by low-lying swamps, rounded and grooved rock exposures, and glacial deposit beaches on many park islands. Following glacial retreat, 500 to 2300 m of water covered the region in the form of glacial Lake Agassiz, and lacustrine deposits now occur throughout the area. The present large lakes of VOYA can be considered remnants of glacial Lake Agassiz (NPS 1973).

Soils

Soil formation has been confined to the last 10,000 years. As a result, podzolization of soils in the area is limited. Soils are rocky and very shallow on the uplands, deeper and organic in the low-lying wet areas. In the sub-basins of Kabetogama Lake glacial erratics are common. Soils are primarily dry, shallow sands or sandy-loams over bedrock on the uplands and midslopes, and moderately well-drained loams on the occasional low-lying level areas (Nelson-Jameson et al. 1986). In general, soil types are interspersed and extremely variable depending on relief (NPS 1973).

The major soil association surrounding the VOYA lakes is the Newfound-Mesaba-Quetico, found on gently rolling to steep uplands. Formed in loamy glacial till, these soils are relatively shallow, have a very thin surface layer of forest litter, are strongly acidic and well-drained. An exception to this are the soils surrounding Kabetogama Lake on the south and west, ie. the Indus-Effie association. These soils are on nearly level lake plains and lake-modified ground moraines. They are formed in the calcareous clayey lacustrine sediments of glacial Lake Agassiz, or in lacustrine modified glacial till. These soils have clay loam sub-layers and are poorly drained.

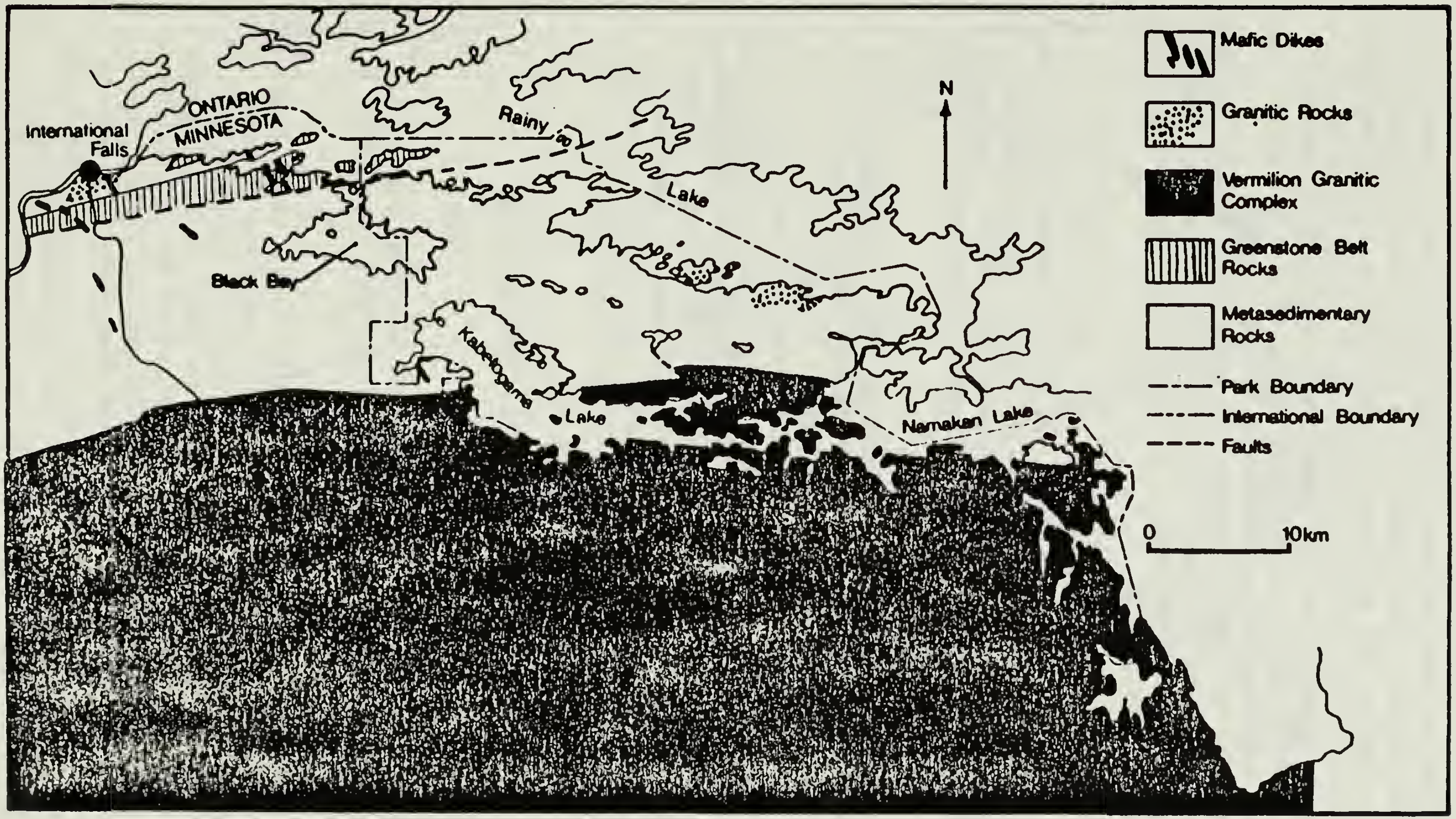


Figure 3. Generalized map of Voyageurs National Park. The mafic dikes are Middle Precambrian in age, about 2,100 million years old; all other rocks are about 2,700 million years old. (After the International Falls 1:250,000 geologic map sheet by D. L. Southwick and R. W. Ojakangas, 1979 .)

Climate

The mid-continental climate of north-central Minnesota is characterized by extreme temperature fluctuations on an annual as well as diurnal basis. The climate is a product of continental polar, maritime polar and maritime tropical air masses. The dry, cold continental polar air mass flowing southward from Canada influences temperature more than precipitation. Collision of these air masses produces disturbances which result in large variations and extremes in weather (NPS 1973). Summer precipitation (45% of annual) normally results from strong, warm, humid air masses moving northward from the Gulf of Mexico; while winter precipitation is the result of the diffuse, cool, westerly flow from the Pacific Ocean.

Winters are typically long and cold, with January mean temperatures ranging from 10.7° C to -22.8° C. Snowfall averages 152 cm, with a maximum of approximately 330 cm, and covers the ground for an average of 140 days per year (NPS 1973). Summers are typically warm and moist, with July mean temperatures ranging from 25.7° C to 11.9° C.

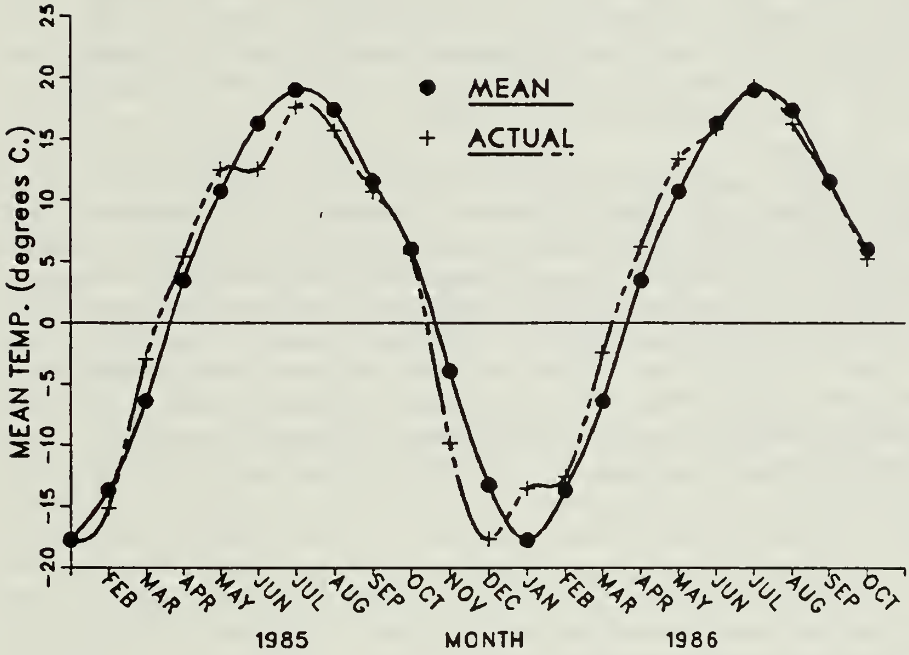
Compared to monthly means calculated since 1951 (National Atmospheric and Oceanographic Administration, International Falls, MN, approximately 20 km W.N.W of the park), spring air temperatures in 1985 and 1986 were higher than average until June (Fig. 4). Following this, temperatures were cooler throughout the fall and winter months until January of 1986 which was much warmer than usual. Summer air temperatures were below average in 1985, but were close to average in 1986. The mean annual temperature for 1985 was 1.39° C., 1.06° C. lower than the long-term average. The cooler year in 1985 is reflected in the total number of monthly cooling degree days.

	1985 Total	1986 Total	"Normal" Total
Cooling ° Days	63	203	216

Where one cooling degree day is accumulated for each degree F. that the daily mean temperature is above some base level (65° F. in this case).

Average annual precipitation at International Falls is 61.8 cm, of which 56.3 cm occurs by the end of October. Snowfall in this region averages approximately 150 cm per year and covers the ground an average of 140 days. Snowfall accounts for 15-20% of mean annual precipitation. Annual precipitation in 1985 amounted to 77.0 cm due to large rains in April, May and June (Fig. 4). Conversely, 1986 was a drier than average year with only 41.9 cm of precipitation falling by the end of October, 14.4 cm less than average. Except for February and April, every month of 1986 experienced lower than expected amounts of precipitation (NOAA 1985, 1986).

MEAN MONTHLY TEMPERATURES (C.)



MEAN MONTHLY PRECIPITATION (cm.)

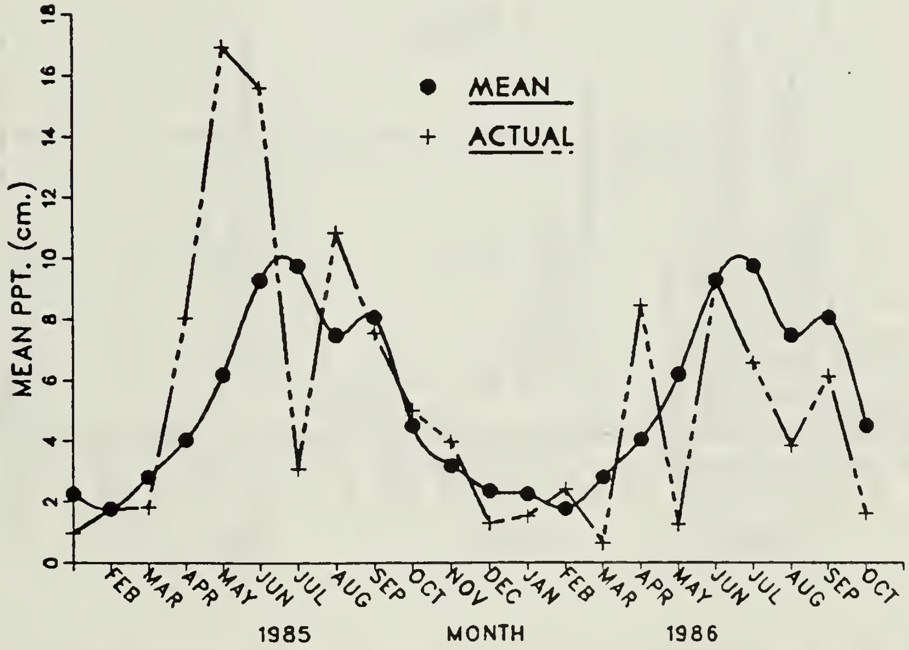


Figure 4. Mean monthly air temperature and precipitation amounts recorded at International Falls, MN (NOAA 1985, 1986).

Mean daily stream discharge data from the Indian Creek watershed which drains into Kabetogama Lake, have been plotted over the 1985-1986 study period (Fig 5). Located between Nebraska and Blind Ash Bays, the brown-water Indian Creek drains a 415 ha steep-sloped watershed containing a beaver pond. Flow (30 cm Parshall flume and Stevens Digital stage height recorder) and water chemistry data have been collected at this site since the summer of 1983 (Nelson-Jameson et al. 1986).

The relatively small, steep-sloped Indian Creek watershed will be more responsive than a larger drainage. However, it is fairly typical of the VOYA lake watersheds. Mean daily discharges during 1986 are typical of sites with a spring melt resulting in a high "one peak" discharge pattern, with roughly 40 to 50% of annual runoff occurring during the months of May and June. The 1985 pattern is less typical due to higher than average precipitation amounts received during May, June and August (Fig. 4) which led to discharge peaks between June and September not observed the following year (Fig. 5).

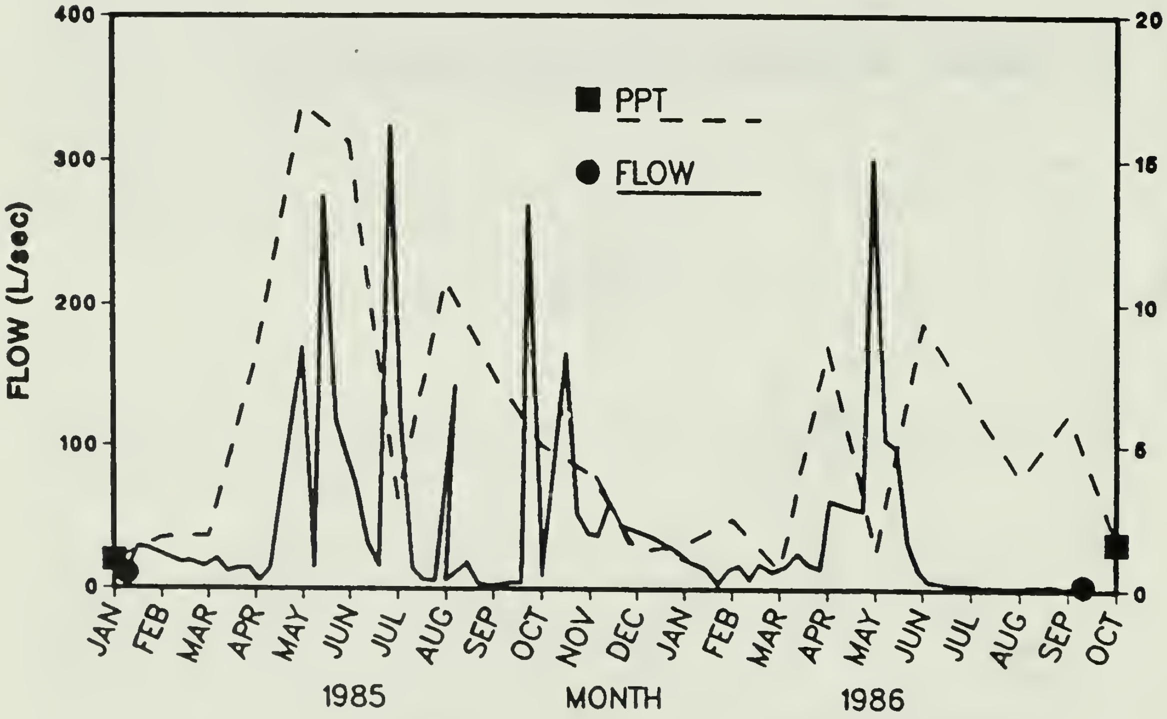


Figure 5. Mean monthly precipitation amounts at International Falls, MN (NOAA data) and stream discharge from the Indian Creek sub-basin of Kabetogama Lake.

METHODS

Eight primary open-water sampling stations, two in each of the four lakes, were established in 1985 (Fig. 1 and Table 1). Stations were located in proximity to sites monitored by the U.S. Department of the Interior Geological Survey (Payne 1978) and to sites similarly sampled in the summers of 1978-80 (Hargis 1981). Monthly grab-sample sites were also established: two in Cranberry Bay of Rainy Lake (CR1 and CR2, Fig. 1), one at Black Bay of Rainy Lake (BB), and one each at Tom Cod Bay and Lost Bay of Kabetogama Lake (TC and LB respectively). In 1986 an additional Kabetogama Lake grab-sample site was established west of Cutover Island (KN). The nearly simultaneous monthly sampling of these stations should allow for detection of temporal changes in local water chemistry and productivity with reference to the remainder of the lake areas.

Monitoring was initiated in the four lakes in May 1985, and continued through October 1986, with emphasis on determining chemical and physical gradients. A synoptic approach to sampling, following Goldman (1974), was employed in an attempt to determine the relative importance of specific sites with respect to the entire lake system. This approach requires simultaneous sampling of multiple stations. Due to the distances involved and weather problems this required sampling all lake stations during a period of about seven to ten days each month during the ice-free field season.

Table 1. Primary open-water sampling stations and approximate locations (see also Fig. 1).

STA	LATITUDE	LONGITUDE	LOCATION
KA	48° 27′ 18′′	93° 00′ 40′′	West-Kabetogama
KB	48° 26′ 35′′	92° 51′ 42′′	East-Kabetogama
NA	48° 26′ 05′′	92° 37′ 10′′	West-Namakan
NB	48° 26′ 25′′	92° 30′ 00′′	East-Namakan
RA	48° 37′ 25′′	93° 09′ 40′′	West-Rainy
RB	48° 36′ 40′′	92° 37′ 15′′	East-Rainy
GB	48° 22′ 50′′	92° 31′ 45′′	Grassy-Bay
SP	48° 21′ 43′′	92° 28′ 38′′	Sand Point

On each visit to a primary sampling station depth profiles for light (LiCor LI-185B spherical underwater quantum sensor), temperature, and dissolved oxygen (DO) (YSI gas analyzer equipped with DO and temperature sensitive probe) were determined. The LiCor instrument is designed to measure Photosynthetically Active Radiation (PAR), a measure of light quantity important in aquatic primary production. PAR is defined as the radiation in the 400 to 700 nm waveband. The PAR observations were recorded in terms of Photosynthetic Photon Flux Density (PPFD), ie., the number of photons of PAR incident per unit time on a unit surface area (μEinst s^{-1} m^{-2}).

Water samples from all stations were collected in a 2.0 liter van-Dorn bottle and retained in acid-washed, deionized-rinsed, 500-ml polyethylene amber bottles that were first double-rinsed with sample water before the final sample volume was retained. Samples were collected at 0.5, 1, 2, 3, 5 and 10 m depths since there was generally no thermal stratification in the water columns. Sixty-ml sub-samples from 1, 3 and 10 m (or 1 m from bottom at shallow water sites) were filtered (0.45-μm Nucleopore), refrigerated, and later analyzed for twelve major ion species on an automated Dionex ion chromatograph at Michigan Technological University (MTU). In this report ion concentrations are given in μeq L^{-1}. Appendix A contains a table of coefficients facilitating conversion of these concentrations to the units of mg L^{-1} which were more commonly used in earlier studies.

During August of 1985 and throughout the entire 1986 field season, additional whole-water samples were collected from 1 and 10 m at all primary stations and retained in glass bottles with Teflon seals. These samples were frozen and later analyzed for total Kjeldahl nitrogen. These samples were digested according to Environmental Protection Agency (EPA) method 351.2-1 (USEPA 1983) and analyzed colorimetrically using an Orion Scientific continuous-flow AutoAnalyzer (Scientific Data product information #116-S397-01). A number of these samples were also analyzed for total organic carbon (non-purgeable) by Zimpro, Inc. (Rothschild, WI) using a Dohrmann DC-80 Carbon Analyzer in accordance with USEPA Method 415.2 (USEPA 1983). Specific conductance (Beckman-Altex conductivity bridge), pH (Corning pH/Tempmeter 4), and bicarbonate alkalinity (0.02N H_2SO_4 titration to pH 4.5 endpoint) were determined at an on-site field lab within 8 hours of sample collection. Conductimeter and pH meter were standardized with external check samples prior to each analytical session in the field.

Primary productivity at the VOYA lake main stations KA, KB, NA, NB, SP, GB, RA and RB was determined monthly using the in situ ^{14}C method (Steemann-Nielsen 1952, Lind 1979, Wetzel and Likens 1979). Samples were taken from four depths within the euphotic zone usually 0.5, 1.0, 3.0, and 5.0 m, or 0.5, 1.0, 2.0, and 3.0 m. Sub-samples from the 2-L van-Dorn were placed into 130 ml ground-glass stoppered DO bottles, and inoculated with 5 μCi $NaH^{14}CO_3$ from pre-measured ampoules using a repeatable auto-syringe. Two light and one dark bottles for each depth were then re-suspended to their original depth by floats and incubated for four hours around midday (approximately 10 AM to 2 PM). Generally, about one half of the full day's photosynthesis occurs during this period. (Wetzel 1975), and these midday incubations result in smaller errors (Vollenweider 1965). Light was measured at the beginning and end of each incubation period. Following incubation, the bottles were retrieved, placed in a light-free chest and transported back to the field lab where the samples were filtered through 47-mm Nucleopore (0.45-µm) filters at low vacuum (< 380-mm Hg) to avoid cell rupturing . The filters were then folded into Whatman Qualitative filters, labelled, dessicated for six hours, exposed to fuming HCl for ten minutes (Williams et al. 1972), and dessicated for an additional four hours. Activity was measured on a Packard Liquid Scintillation Spectrophotometer at MTU, and carbon assimilation rates were calculated following the procedures of Wetzel and Likens (1979).

Chlorophyll-*a* was determined spectrophotometrically as outlined in Standard Methods (1980) and modified for DMSO extraction per Burnison (1980). Three-hundred ml sub-samples from each depth were filtered through 47-mm Gelman Acetate filters (0.45-µm) at less than 380-mm Hg vacuum. Magnesium carbonate was not added during filtration (Holm-Hansen and Riemann 1978). Filters were then folded into Whatman Qualitative filters, labeled, and stored frozen in Whirl-pac bags until analyzed at MTU. At MTU the acetate filters were dissolved in 4.0-ml of reagent grade dimethyl sulfoxide (DMSO) and heated in a 60 C hot water bath for 10 minutes to speed extraction. Samples were then brought up to 10-ml with 90% acetone, agitated on a Vortex mixer, and centrifuged for 10 minutes. The supernatant was decanted to cuvettes and absorbance was determined on a Beckman DU-8 spectrophotometer at 750, 665, 645 and 630-nm wavelengths. Following the initial reading, 30-µl of 4N HCl was added directly to the cuvette and the samples re-read to correct for overestimation due to phaeophytin. Chlorophyll-*a* concentrations in this report were calculated using tri-chromatic equations (Strickland and Parsons 1972, Meeks 1974).

On each sampling date in 1985, 500-ml whole water samples were collected for plankton analysis. Samples were+ immediately fixed with Lugol's solution (Lind 1979) and stored in 500-ml polyethylene amber bottles. August 1985 samples have been examined for qualitative characterization, but nearly all presently await more detailed analysis and quantification at MTU.

Laboratory Quality Control

Routine quality assurance steps include the following: For each block of samples run on the ion chromatograph, cations are summed and plotted against specific conductance to detect outliers. Any outliers are checked, and if not accounted for, are rerun. Use of an automated system minimizes accidental sample inversion, the most common source of outliers. Other primary steps taken with each sample block include: use of National Bureau of Standards reference standards (cation and acid precipitation standards), replication (5% with low, medium, and high concentration replication), and analysis of split weekly National Atmospheric Deposition Program (NADP) samples with results compared with the NADP Central Analytical Laboratory. This laboratory also participates in the National Acid Precipitation Assessment Program (NAPAP) quality assurance program which includes routine analysis of inorganic "blind" quality assurance samples, and testing of pH and specific conductance equipment. Additional laboratory and data handling steps are taken, and are outlined in further detail in Stottlemyer (1987).

RESULTS AND DISCUSSION

Physical Characteristics

Lake Morphometry:

The distribution of phytoplankton and productivity in a lake are directly related to the morphological features of the lake basin. Lakes in the VOYA system span a wide range of basin shapes, sizes, volume/area ratios, mean and maximum depths (Table 2).

Table 2. Morphometric parameters for Kabetogama, Namakan, Rainy, and Sand Point Lakes at full capacity.

	Kabetogama	Namakan	Rainy	Sand Pt.
Lake Area (ha)	9800	10000	89000	3400
Island area (ha)	862	1191	-----	156
Drainage Basin (ha)	63000	1900000	1900000	-----
Max. depth (m)	15.2	36.6	49.1	56.1
Mean depth (m)	9.1	14.9	9.9	13.1
Length (km)	24.1	25.7	74.0	14.5
Volume (10^6 m^3)	895	1503	8530	446

Some of the detailed bathymetric map work required for evaluation of major morphological parameters has already been performed by Prof. Wayne Meyers, School of Forestry, Pennsylvania State University. Depth-volume curves for Kabetogama, Namakan, and Sand Point Lakes, illustrate the major differences between these three lakes and the impact of depth reductions on their respective volumes (Fig. 6). Reduction in water level of three meters from full capacity decreases the volumes of Namakan, Sand Point and Kabetogama Lakes by approximately 20, 23 and 34% respectively, while exposing 17, 24 and 25% of their respective bottom areas.

A strong relationship between lake morphology and biological productivity has been found in many other studies (Rawson 1952, 1955, 1956, Hayes and Anthony 1964, Sakamoto 1966), and these VOYA drawdown curves suggest such a relationship exists for these lakes. It has been proposed that production should be proportional to the drainage basin area divided by the lake volume (Schindler 1971). In accordance with this concept, mean depth is often inversely correlated with productivity at all trophic levels (Wetzel 1975). Rawson (1953) concluded that morphometric factors, particularly mean depth, showed a significant relationship with

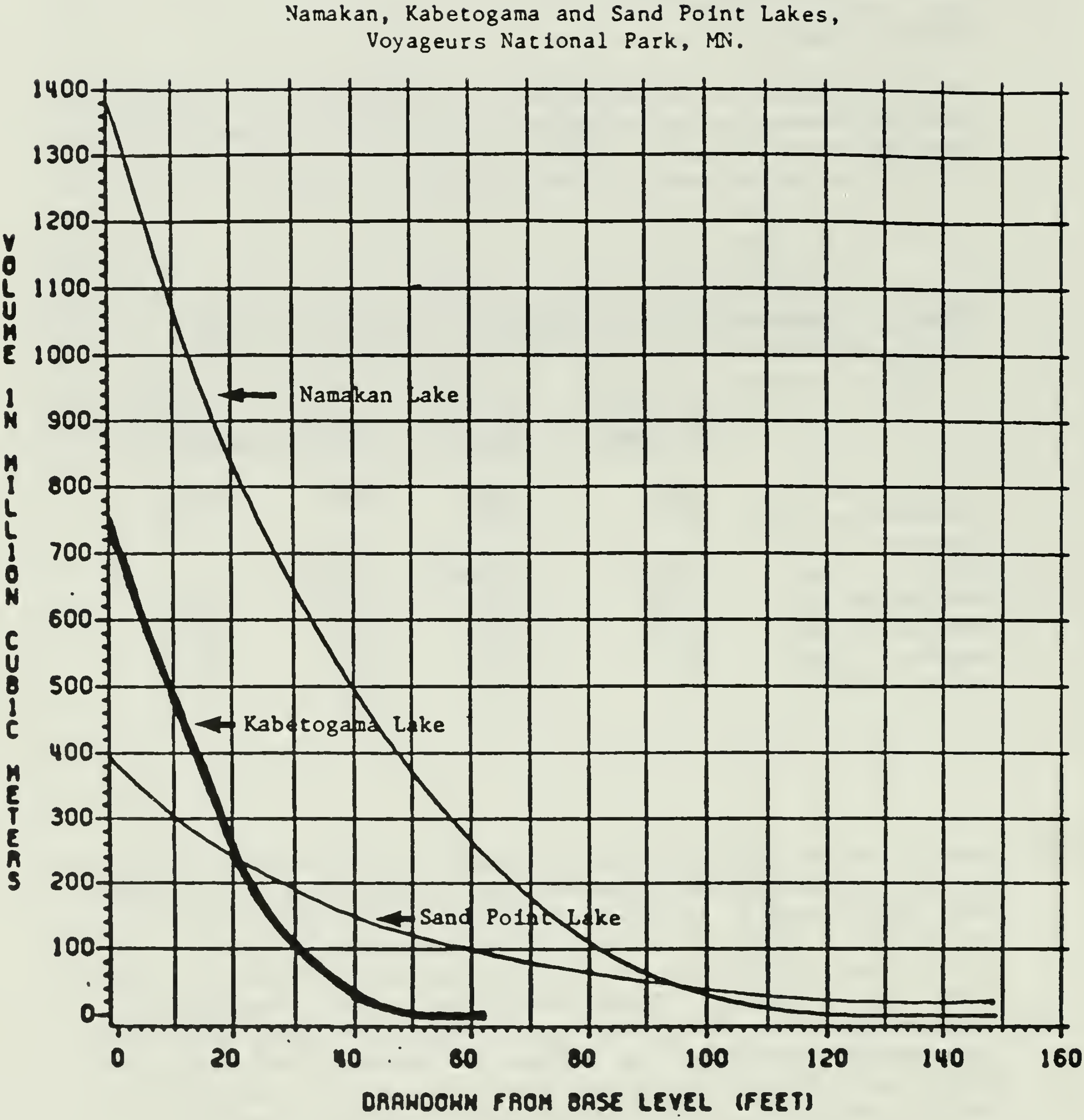


Figure 6. Drawdown curves for Namakan, Sand Point, and Kabetogama Lakes, Voyageurs National Park, MN (Dr. Wayne Meyers, School of Forestry, The Pennsylvania State University, University Park, PA).

phytoplankton standing crops. Others have failed to verify this conclusion (Northcote and Larkin 1956). Some results have suggested that when lakes of similar nutrient and energy status are compared, deep lakes have roughly the same phytoplankton production per unit area as shallow ones (Brylinsky and Mann 1973). Yet on the basis of production per unit volume, shallower lakes would be more productive and would be expected to have higher densities of phytoplankton. As Brylinsky and Mann (1973) explain, it is reasonable for us to consider "shallow lakes as compressed versions of deep lakes, in terms of productivity per unit area."

Generally stated, shallower lakes tend towards greater productivity than deeper lakes. It is believed that lake depth has a significant influence on productivity, based upon the assumption that nutrients are used more efficiently in shallow systems. Lake sediments are reservoirs as well as sinks for nutrients, therefore the shallower the water overlying the bottom sediments, the greater the amount of nutrients recycled from this source per unit volume of water will be. Wave induced stirring of sediments associated with low mean depth would facilitate such processes (Oglesby 1977). Although morphometry is only one influencing parameter, we might expect Kabetogama to be a more productive lake based solely upon its shallower basin. The possibility that drawdown and accompanying volume reductions of VOYA lakes enhances phytoplankton production through nutrient concentration effects is discussed later.

Water Temperature:

Temperature exerts fundamental effects on limnological phenomena such as lake stability, gas solubility, and biotic metabolism. Temperature data are most frequently presented as depth-temperature plots (Appendix B). The definition of a thermocline is the depth where temperature drops 1° C or more for each 1 m change in depth. The plots in Appendix B use equal arithmetic units on each axis. Any slope equal to or greater than 45° from the vertical may be loosely defined as a thermocline.

For all stations, water temperature increased through May, June and July, decreased slightly in August and September, and then decreased by a relatively large amount in October. Mean water column temperatures differed by as much as 10° C between September and October, as much, or more than the variation between May lows and July peak temperatures. Note the large difference in temperatures recorded in May of 1985 and 1986 (Fig. 7). Temperature data were collected May 28-31 in 1985, but much earlier in the month (May 5-11) in 1986. Obviously there is a large change in mean water column temperature from ice-out in April until the end of May especially for these relatively shallow lakes.

Figure 7. Mean water column temperatures (0 - 10 m) for the main lake stations, Voyageurs National Park, MN.

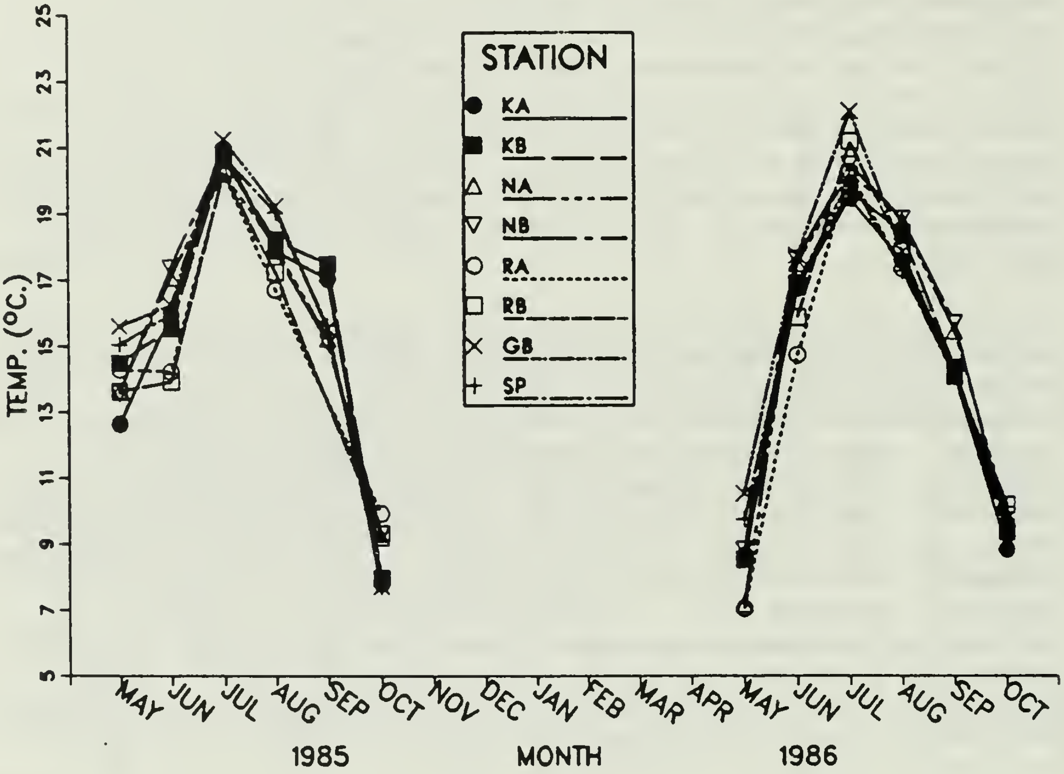


Table 3. Depths of thermal stratification (m) at the eight primary sampling stations during 1985 and 1986, Voyageurs National Park, MN.

		Station							
		KA	KB	NA	NB	RA	RB	GB	SP
	Month-(date)								
1985									
	May (28-31)		2		7	3	3	5	11
	June (26-30)								13
	July (14-23)			8		10			
	Aug. (20-25)								11
1986									
	May (05-11)								
	June (11-16)	4		9	7	10		2	7
	July (14-18)			13		11		5	8
	Aug. (25-31)					10			10

Temperature profiles indicate an absence of any long-term stratification in Kabetogama (Table 3). The east Kabetogama station (KB) did stratify in May 1985, and the west Kabetogama station (KA) in June 1986. It may appear that deep thermal stratification occurred in July at station KB. However, possible contact between the temperature probe and bottom sediments makes inference of stratification based on bottom points risky. If Kabetogama does stratify intermittently throughout the summer, it is probably of short duration and only following extended periods of calm, warm weather. Kabetogama's lack of strong summer stratification is a function of its relatively shallow basin and alignment of long axis to the prevailing winds.

Namakan Lake stations show that waters were not well-mixed in May 1985, but became increasingly so by July. At this time a sharp thermocline developed in west Namakan (NA). By the middle of August this thermocline had disappeared. Temperatures in September did not vary by >0.5° C through the entire water column. Temperature profiles for October 1985 in Namakan were not obtained. However, isothermal conditions at approximately 8° C seem most likely. May 1986 temperatures near the bottom at NA (5.6° C) were the lowest observed during the study. Stratification was observed in June and July at station NA during 1986, but only in June at station NB.

Sand Point is the only lake which appears to stratify for more than a few weeks at a time. Between May and June 1985, surface water temperatures remained the same, but deeper depths warmed by as much as 8°C. In July, station SP exhibited a divergence from the typical pattern of summer stratification. This pattern, marked by the formation of multiple discontinuity layers, seems common in the VOYA lakes (see also RA and NA in July 1985, Appendix B). This type of situation usually lasts only a week or less, and is common when intense heating alternates with periods of extensive mixing (Wetzel 1975). Mixing of the entire epilimnion may cease during a calm, hot period, during which surface waters can be intensely heated and are mixed by light breezes for only one or two meters in depth. In this way secondary metalimnia form, overlying the primary thermocline. These multiple metalimnia are unstable and break down easily with later periods of cooling and wind-generated mixing. A thermocline at approximately 11 m was observed at SP again in August 1985, but disappeared by the middle of September and the onset of fall overturn. As with all other lakes, temperatures were quite consistent through the water column in October of both years. Stratification was continuous at increasing depths throughout June, July and August of 1986. Temperature profiles for the shallower Grassy Bay (GB) sampling station are also provided, but show little summer thermal stratification.

Rainy Lake (RA and RB) temperature profiles are similar to those for SP (Appendix B), although there is no thermocline present at either Rainy Lake station in June or August 1985, as was present at SP. September 1985 temperature profiles in Rainy Lake were not obtained due to poor weather conditions. October profiles during both 1985 and 1986 show consistently lower temperatures and a high degree of mixing characteristic of all sampling stations by this month. Station RB showed no stratification at all in 1986, while station RA was stratified throughout June, July and August of that year.

Temperature profile data seem to indicate that thermal stratification is infrequent and unstable in these lakes. However, profiles taken at stations where waters are deeper show that stratification does occur in Sand Point, Namakan and Rainy Lakes every summer, but at depths greater than those found at the main sampling stations of this study (Larry Kallemeyn, Voyageurs National Park, pers. comm.).

Mean temperatures for the upper ten meters at all stations increased slightly between late-May and late-June of 1985, but increased dramatically between early-May and early-June of 1986 (Fig. 7) largely the result of wind action and increasing air temperatures. Mean temperatures at all stations then decreased by two or three degrees in August and less in September of both years. The sharpest change in mean water column temperatures occurred between September and October. Mean temperatures at stations RA and RB are not available for September 1985; thus, Figure 7 does not accurately reflect temperature variation between August and October at these stations. Poor weather also prevented temperature data from being collected at RA in September 1986.

Dissolved Oxygen:

The dissolved oxygen (DO) content of lake waters is a function of the metabolic activities of open water and benthic organisms, the diffusion gradient at the air-water interface, and DO distribution by wind-driven mixing. In general, 3 mg L^{-1} DO or less is considered stressful to aquatic vertebrates (Lind 1979). All lakes in the VOYA system appear to be well-oxygenated throughout the summer months, although anaerobic conditions may exist in bottom sediments or just at the sediment-water interface (Appendix C). Data on DO are not available for the first two sampling periods (May and June 1985) at any station, nor for Rainy Lake in September 1985, Namakan Lake in October 1985, and west Rainy (RA) in September 1986.

Sharp decreases in DO at depth are the result of contact between the DO probe and bottom sediments. Only at station SP was a decrease in DO observed long before bottom sediments were approached. This was in both July and August of both years. There is no additional evidence to suggest that hypolimnetic anoxia occurred for any substantial period of time during the six-month sample period.

The inverse relationship between water temperature and oxygen solubility is apparent in the strong negative correlation (Spearman rank correlation coefficient (R^2) = -0.648, $P < .001$, n = 615) between temperature (°C) and DO (mg L^{-1}). Consistent with the findings in this study, waters stained with humic organics were found undersaturated with O_2 (Wetzel 1975). Throughout our study, DO concentrations less than 6.0 mg L^{-1} rarely appeared, but the typical orthograde O_2 distribution was not encountered. The lack of sharp boundaries in vertical DO distributions likely results from the rarity of extensive thermal stratification between May and October.

Light Extinction:

The vertical light extinction coefficient is commonly determined from the percentile absorption of light at the surface (0 m) over depth. Calculations of the vertical extinction coefficient (VEC) are not very reliable in the first meter below the surface due to surface agitation in the form of ripples and waves. Therefore, average calculations for the eight primary stations have been made excluding values from the top meter. Mean 1985 VEC's for 1-5 m at the eight primary sampling stations are presented in Table 4. Values for each 1 meter interval were calculated from the Birgean percentile absorption equation: VEC = $\ln I_o - \ln I_z$, where I_o = irradiance at lake surface, and I_z = irradiance at depth z (Lind 1979). Vertical extinction coefficient values for natural lake waters vary from around 0.2 (80% transmission per meter) in unusually clear lakes, such as Lake Tahoe, California, and Crater Lake, Oregon, to about 4.0 in highly stained lake waters or lakes with high biogenic turbidity. In extremely turbid water (eg., in reservoirs near major river inflows under flood conditions, or in lakes receiving fine materials such as volcanic ash) VEC's in excess of 10.0 are common (Wetzel, 1975). On the basis of percent transmittance of light through the water column (%T), all four lakes considered in this study have been classified as medium clarity lakes (%T = 17-40, Hargis 1981).

Table 4. Mean monthly vertical light extinction coefficients (VEC) for 1985, 1-5 m, for eight sampling stations, Voyageurs National Park.

	Stations							
Month	KA	KB	NA	NB	RA	RB	GB	SP
May	7.52	5.71	7.80	6.14	8.12	7.53	5.06	5.19
June	8.67	5.08	7.92	6.65	3.79	6.45	4.48	4.44
July	8.43	7.14	8.36	7.26	7.53	7.89	5.74	6.39
Aug.	7.17	7.76	7.35	7.48	5.63	8.03	5.83	6.22
Sept.	7.80	6.93	7.30	5.26	6.06	6.03	5.44	5.80
Oct.	7.51	6.30	6.100	5.00	6.50	----	5.32	5.34

In 1985, mean VEC's (1-5 m) ranged from 3.80 (RA June) to 8.43 (KA July). Phytoplankton standing crops, which are indicated by chlorophyll-a (chl-a) concentrations, do not appear to be the significant factor influencing light penetration. Combining 1985 and 1986 data failed to yield a significant correlation between photosynthetic photon flux density (PPFD) and algal biomass (as chl-a), despite previous description of a strong negative correlation between %T and chl-a (multiple linear regression analysis for 24 VOYA lakes, $R = -.570$, Hargis 1981). Vertical extinction coefficient values indicate that the degree of cloudiness, stain or color, or amount of wave action are more influential than algal density in regulating light penetration. However, a significant relationship existed between PPFD and ^{12}C-assimilation (Spearman rank correlation $P < .001$, $n = 275$).

In addition, diurnal solar radiation input was measured on July 2 and 21, 1985. Readings taken at 15 minute intervals from 8:00 AM to 4:30 PM reveal that 61 and 57%, respectively, of total daily solar radiation occurred during the usual ^{14}C incubation period (10 AM to 2 PM). These day-to-day differences in solar radiation have not been taken into account in the primary productivity (^{12}C-assimilation) data presented later. Appendix D contains monthly plots, for each sampling station, of mean PPFD values (1 m above surface, surface, 0.5, 1, 2, 3, 4, and 5m below surface). Note that these mean values are highly influenced by factors other than water clarity (time of day, cloud cover, etc.).

Chemical Characteristics

Seasonal Inputs:

The chemistry of water entering a watershed as precipitation is greatly modified before reaching tributaries and lakes. For example, mean volume-weighted pH of precipitation at VOYA is 4.95, while over the same time period a typical tributary to Kabetogama Lake had a mean volume-weighted pH of 7.15 (Nelson-Jameson et al. 1986). Table 5 presents mean monthly volume-weighted ion concentrations for precipitation (National Atmospheric Deposition Program/National Trends Network, Marcell Experimental Forest, roughly 100 km south of VOYA), streamwater (Great Lakes Area Resource Studies Unit (GLARSU) monitored Indian Creek tributary to Kabetogama Lake), and lake (station KB, the main lake station in this study located closest to Indian Creek).

Hydrogen ion and nitrate clearly are retained in the system before reaching the stream. Nitrate retention is probably due to uptake by terrestrial vegetation within the watershed (Armstrong and Schindler 1971). Streamwater concentrations of sulfate generally reflect those of precipitation (Fig. 8), while calcium in streamwater appears to be inversely related to precipitation concentrations (Fig. 9). Concentrations of major base cations in surface runoff (Ca^{+2} and Mg^{+2} in this case) should be higher than in precipitation because of decomposition and solution processes in soils, glacial drift minerals, and exposed bedrock (Likens et al. 1967, Schindler and Nighswander 1970, Armstrong and Schindler 1971, Brunskill et al. 1971). Note that Indian Creek Ca^{+2} concentrations decreased relative to the much lower precipitation concentrations during high discharge periods (Figs. 9 and 5).

The dominant anion in Indian Creek streamwater is bicarbonate, while calcium is the dominant cation. Cation/anion balances for Indian Creek show an anion deficiency, likely attributable to dissolved organic acids in this brown-water stream. Sulfate (11 kg ha^{-1} yr^{-1}) and nitrate loadings (12 kg ha^{-1} yr^{-1}) at VOYA are the lowest which were found of five parks in the Great Lakes basin (Nelson-Jameson et al. 1986). While precipitation in the VOYA area is altered by anthropic sources, degradation of precipitation quality and its subsequent effects are probably minimal relative to the Great Lakes region as a whole.

Data on precipitation and water discharge inputs of nutrient and other ions illustrates the large month-to-month and yearly variability that occurs in the Indian Creek watershed. This would indicate that two years of data may not be sufficient to characterize nutrient loadings into these lakes. This should be kept in mind in any future attempts to model nutrient concentrations or their effects on this or similar systems.

Table 5. Mean monthly volume-weighted ion concentrations (μeq L^{-1}) for precipitation (NADP/NTN, Marcell Experimental Forest), runoff (GLARSU, Indian Creek tributary to Kabetogama Lake), and lake water (station KB).

Ion	Year	Month	Ppt.	Stream	Lake
Ca^{+2}					
	1985	May	14.50	295.80	497.50
		June	10.42	266.80	367.16
		July	11.59	291.63	425.90
		Aug.	10.02	268.64	399.90
		Sep.	10.06	364.91	356.88
		Oct.	3.70	311.62	
	1986	May	7.99	357.30	555.24
		June	19.03	395.14	529.79
		July	10.84	433.85	551.20
		Aug.	3.87	531.90	475.35
		Sep.	3.42	443.74	654.49
		Oct.	7.47		576.99
K^{+}					
	1985	May	1.07	17.10	22.90
		June	0.94	9.99	20.29
		July	0.82	6.36	21.29
		Aug.	0.61	7.24	20.12
		Sep.	0.75	15.41	20.17
		Oct.	0.37	12.00	
	1986	May	0.88	12.05	23.50
		June	0.79	8.51	17.69
		July	0.76	9.59	16.51
		Aug.	0.27	12.75	14.26
		Sep.	0.33	9.70	15.96
		Oct.	0.71		16.34
H^{+}					
	1985	May	8.74	1.01	0.31
		June	4.26	0.50	0.55
		July	3.95	0.46	0.08
		Aug.	9.79	0.41	0.13
		Sep.	8.71	0.53	0.07
		Oct.	13.04	0.34	
	1986	May	9.88	0.31	0.13
		June	2.22	0.55	0.04
		July	3.84	0.36	0.09
		Aug.	8.02	0.42	0.15
		Sep.	18.60	0.42	0.05
		Oct.	9.87		0.29
SO_4^{-2}	1985	May	30.44	39.05	64.47
		June	16.81	14.78	71.79
		July	21.67	14.29	66.29
		Aug.	23.48	6.68	67.91
		Sep.	30.35	15.98	67.95
		Oct.	15.95	26.86	
	1986	May	22.68	28.57	60.80
		June	28.05	11.65	54.68
		July	15.41	9.79	60.20
		Aug.	11.36	12.50	59.12
		Sep.	30.46	7.89	57.91
		Oct.	25.43		41.35
NO_3^{-}	1985	May	22.18	0.35	1.03
		June	13.12	1.62	2.04
		July	12.52	2.13	0.97
		Aug.	14.03	1.01	0.97
		Sep.	14.80	1.23	0.00
		Oct.	11.78	0.68	
	1986	May	8.93	0.86	0.95
		June	26.78	10.39	0.36
		July	14.16	13.94	0.87
		Aug.	7.46	23.99	0.18
		Sep.	11.07	11.17	0.00
		Oct.	15.23		0.92

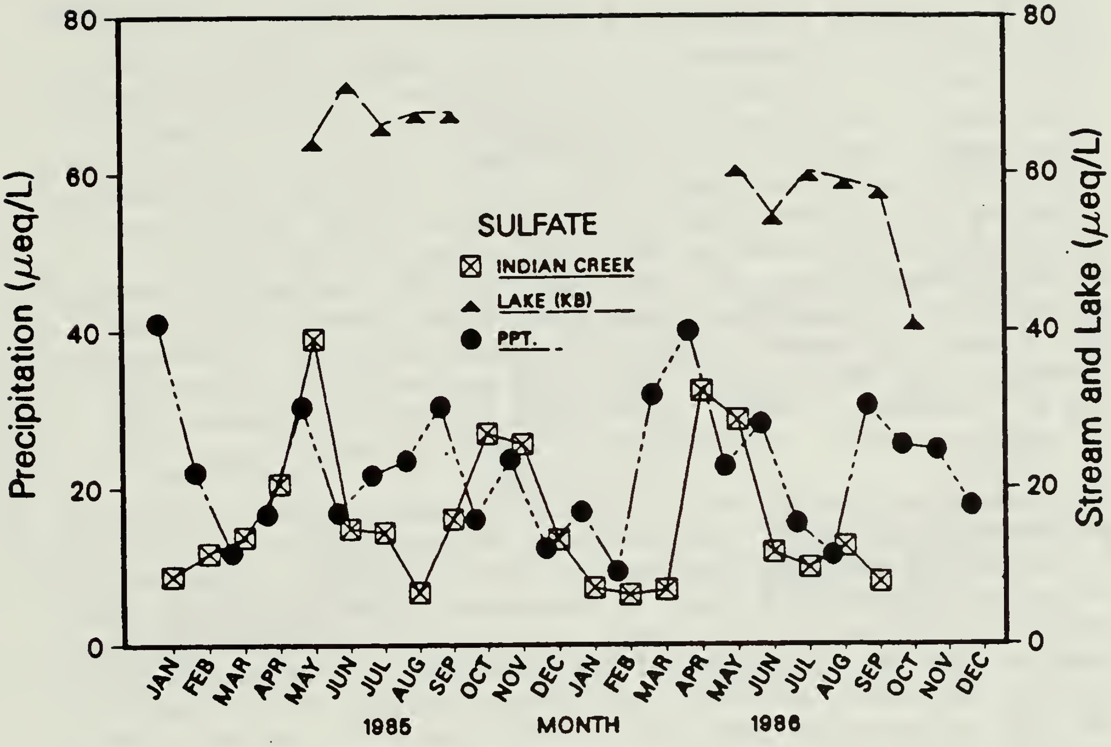


Figure 8. Mean monthly volume-weighted precipitation and Indian Creek SO_4^{-2} concentrations compared to mean in-lake (KB) concentrations for 1985 and 1986.

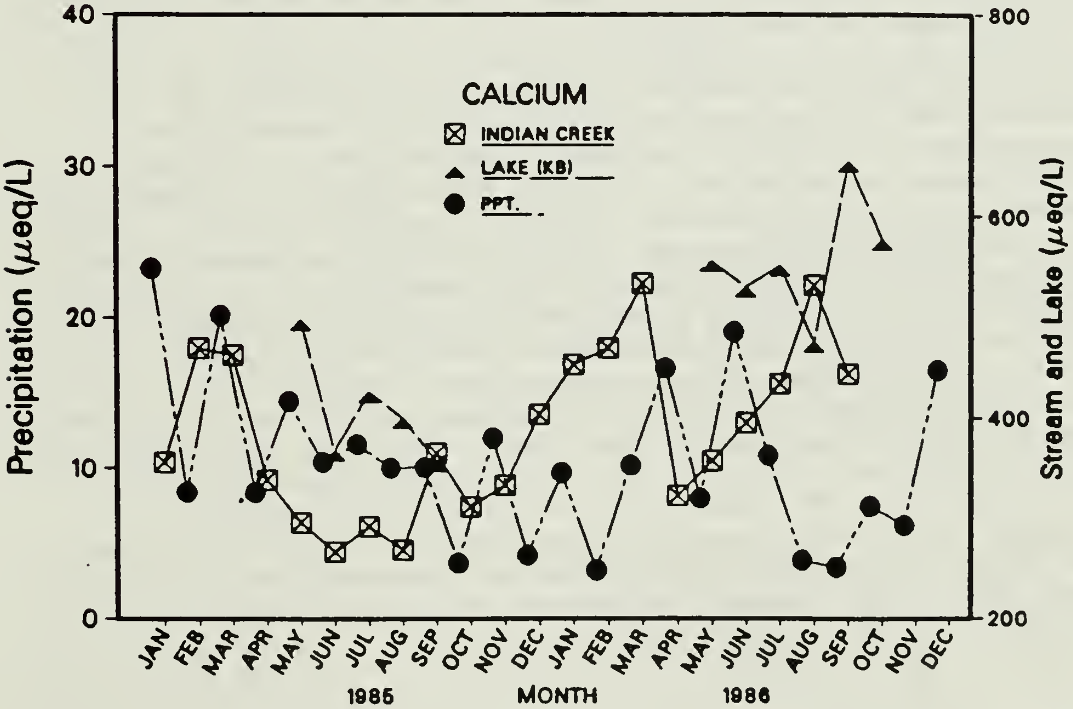


Figure 9. Mean monthly volume-weighted precipitation and Indian Creek Ca^{+2} concentrations compared to mean in-lake (KB) concentrations for 1985 and 1986.

Calcium:

Calcium (Ca^{+2}) is important to biological productivity in lake waters, and it is considered a macronutrient. Lakes having Ca^{+2} concentrations of 10 mg L^{-1} (499 μeq L^{-1}) or less are usually oligotrophic, whereas waters with 25 mg L^{-1} (1247.5 μeq L^{-1}) are usually distinctly eutrophic (Lind 1979). Calcium concentrations presented in the 1986 Progress Report (Kepner and Stottlemyer 1986) were in error due to laboratory bias, but have been corrected here. Mean Ca^{+2} concentrations for the upper 10 meters at the Rainy, Namakan and Sand Point primary sampling stations were always within the oligotrophic range (Fig. 10). Kabetogama stations were the exception with Ca^{+2} concentrations up to 753.6 μeq L^{-1} (KA Sept., 1986). Kabetogama stations also showed the greatest variation in mean monthly concentrations.

The lowest Ca^{+2} levels were recorded at station NA for all months except September 1985, when levels at NB were slightly (4.8 μeq L^{-1}) lower, and October 1986 when NA had the highest concentration of all stations except those in Kabetogama. As expected, between-station relationships and change over time in Ca^{+2} concentration parallel changes in both alkalinity and conductivity to a large degree. As with alkalinity, Ca^{+2} concentrations were higher at all lake stations in 1986 (mean = 396.4 μeq L^{-1}) than 1985 (282.7 μeq L^{-1}), particularly at the Kabetogama stations. Trends in Ca^{+2} during 1985 suggest that Kabetogama received proportionally more runoff than the other lakes. Other stations in 1985 and all stations in 1986 appear to be reflecting increased concentrations with increased evaporation or lesser dilution accompanying reduced runoff volumes in 1986 (Fig. 5).

Usually the amount of calcium utilized by phytoplankton is small in comparison to that available, thus seasonal concentration patterns are not obviously related to productivity. The sharp drop in mean concentration at station KB originally observed between August and September, 1985 (399.9 to 287.7 μeq L^{-1}, Kepner and Stottlemyer 1986) was due to two outlying data points which have been struck from the ion chemistry data set. A similar decrease in the SO_4^{-2}, Mg^{+2}, Na^+ and K^+ concentrations was also observed at station KB in September of 1985, but has been corrected by removing the anomalous points. Mean Ca^{+2} concentrations for June, July and September of 1973 (NPS 1973) at Meadwood Bay (sites located quite close to present station KB) were recorded as 2.75, 2.01, and 3.38 mg L^{-1}, respectively (ie., 137.2, 100.3 and 168.7 μeq L^{-1}). These results indicate an increase in September concentrations, as occurred in 1986 at KB, but are less than present concentrations by roughly three-fold. These data further suggest differences in year-to-year precipitation input and dilution.

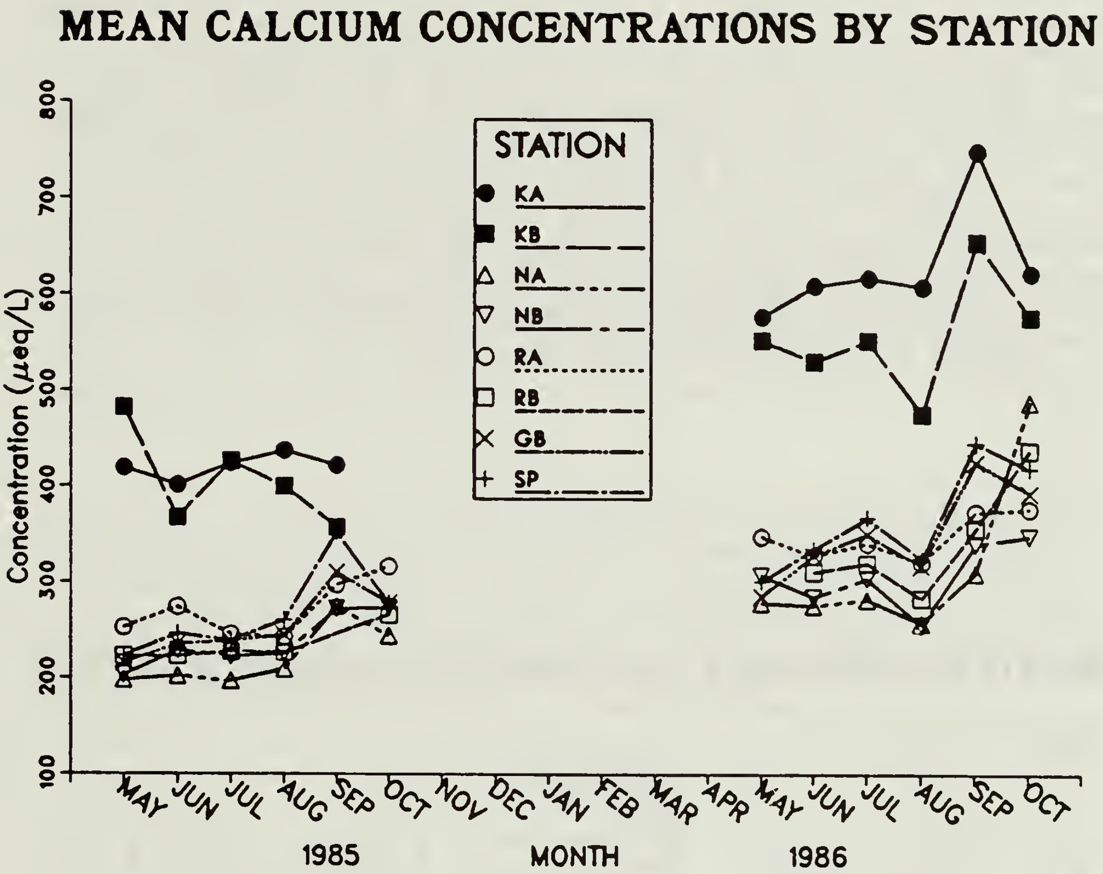


Figure 10. Mean calcium concentrations (µeq L^{-1}) for main lake stations (1, 3, and 10 m), Voyageurs National Park.

Magnesium:

Although magnesium (Mg^{+2}) is required by all chlorophyllous organisms, it is generally not a limiting nutrient in fresh waters (Wetzel 1975). As with chloride, Mg^{+2} is relatively conservative and concentrations do not fluctuate extensively. In rare instances Mg^{+2} may be a factor influencing phytoplanktonic productivity in extremely oligotrophic systems (Goldman 1960). This does not seem to be the case in the VOYA lakes where Mg^{+2} and Ca^{+2} are the dominant cations.

Magnesium concentrations were higher in Kabetogama than in other lakes throughout both sampling seasons (Fig. 11). The eight-station mean Mg^{+2} concentration for 1985 was 232.4 µeq L^{-1} and for 1986, 281.6 µeq L^{-1}. The range of concentrations for all waters sampled was from 80.4 to 528.9 µeq L^{-1}. The seasonal gain in Mg^{+2} concentration at most stations coincided with reductions in runoff, particularly in August and September of both 1985 and 1986 (Fig. 5).

The concentration of Mg^{+2} in oligotrophic Clear Lake, Ontario surface waters (May 1968) was 57 µeq L^{-1} (Schindler and Nighswander 1970). The mean for 40 lakes in the Experimental Lakes Area (ELA) was 74.1 µeq L^{-1} (Armstrong and Schindler 1971). The present study finds a higher mean of 387.8 µeq L^{-1} for station KB. Finally, a decimal error is suspected in the mean values given for June, July, and September at Meadwood Bay (22.2, 27.2, and 172.8 µeq L^{-1}, NPS 1973). More dilute freshwaters have concentrations even higher than these: Lake Superior, 230.4 (Beeton and Chandler 1963); Lake of the Woods, 296.3 (Thomas 1959); and, in fact the world average of freshwater lakes is 337.4 (Livingstone 1963, all concentrations in µeq L^{-1}).

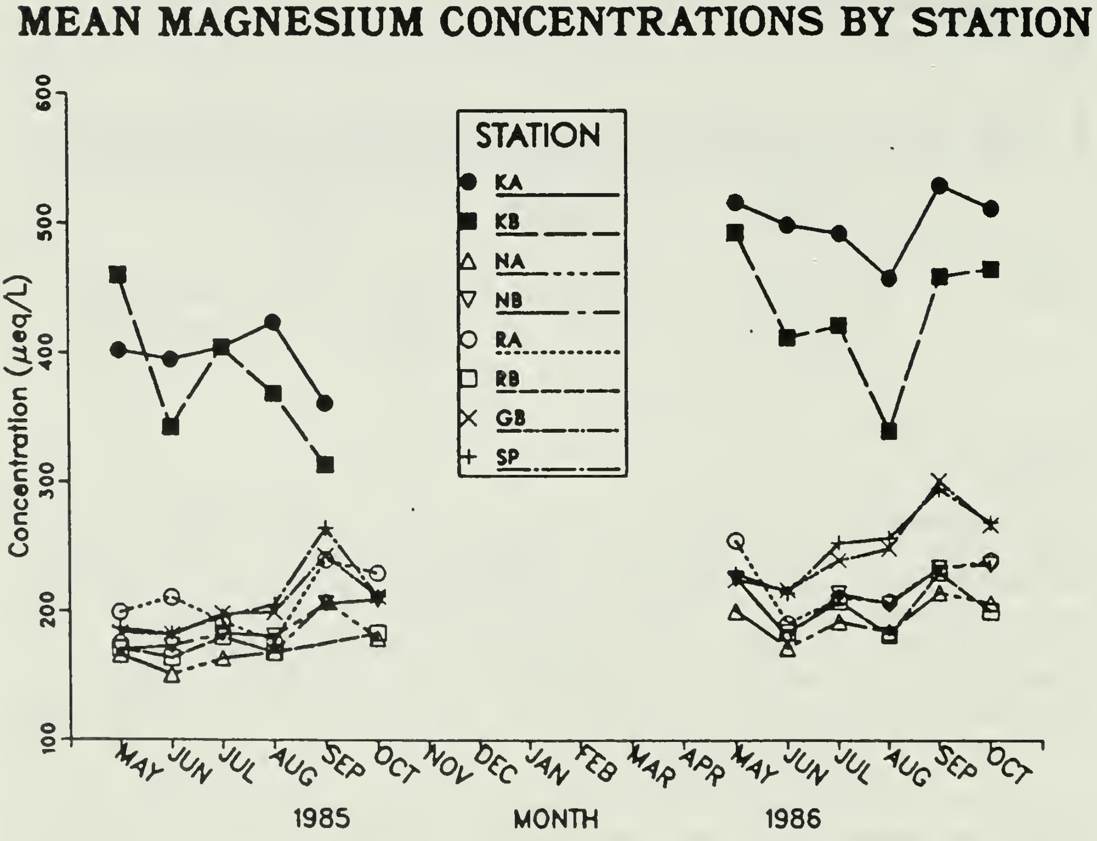


Figure 11. Mean magnesium concentrations (µeq L^{-1}) for main lake stations (1, 3, and 10 m), Voyageurs National Park.

Sodium and Potassium:

Sodium (Na^+) is another of the more conservative cations, and therefore exhibits very little spatial and seasonal variation attributable to biological activity in most lake waters. Although potassium (K^+) may be a limiting nutrient in rare cases and epilimnetic reduction in K^+ has been observed in extremely productive lakes (Wetzel 1975), both Na^+ and K^+ usually occur abundantly as highly soluble cations of numerous salts, and alteration of concentrations in natural waters due to biotic activity, particularly algal primary production, is uncommon (Wetzel 1975). This seems to be the case for the VOYA primary sampling stations, as Na^+ and K^+ are found at high concentrations relative to biological need.

The mean Na^+ concentrations in 1985 ranged from 44.1 (RB July) to 68.9 μeq L^{-1} (SP June), and K^+ concentrations ranged from 10.3 (KB September) to 24.4 μeq L^{-1} (SP May). In general, stations in Rainy and Namakan Lakes had lower concentrations of both cations, although the east Namakan station (NB) exhibited peaks in October of both years in the concentrations of both Na^+ and K^+ (Figs. 12 and 13). Sand Point concentrations were higher than others, particularly for Na^+ in 1986. In 1986, Na^+ peaks occurred in September at all non-Rainy Lake stations except NB, while K^+ peaks at the same time occurred only at KA, GB, and NA. The seasonal trends in Na^+ concentrations, most apparent for stations NA, GB and SP in 1986, probably reflect reduced dilution accompanying reduced runoff or increased evaporation. The reduced K^+ concentrations evident in August 1986 at all sites probably reflect biological uptake. Concentrations for the Kabetogama stations were usually intermediate between those for Sand Point (SP and GB) and those for Namakan and Rainy Lakes. The relative differences noted for these cations probably reflect differences in bedrock character.

For the eight primary sampling sites Na^+ concentrations ranged from 12.9 to 87.0 (mean = 57.0 μeq L^{-1}), and K^+ from 5.2 to 26.8 (mean = 17.6 μeq L^{-1}). For comparative purposes, Na^+ concentrations in the range 17.40 to 73.95 μeq L^{-1}, mean = 39.15 (n = 40) and K^+ concentrations in the range 5.11 to 25.57 μeq L^{-1}, mean = 10.24 (n = 40), were observed in the ELA of northwestern Ontario (Armstrong and Schindler 1971). In May of 1968, Clear Lake concentrations of Na^+ and K^+ were 32 and 12 μeq L^{-1} respectively (Schindler and Nighswander 1970). The averages cited for all freshwater bodies are 274 μeq L^{-1} (Na^+), and 59 μeq L^{-1} (K^+) (Livingstone 1963). Mean Na^+ concentration for Meadwood Bay was found to be 89.3 μeq L^{-1} (NPS 1973). Station KB, located near Meadwood Bay, had concentrations ranging from 12.9 to 67.4, with a mean of 52.1 μeq L^{-1}.

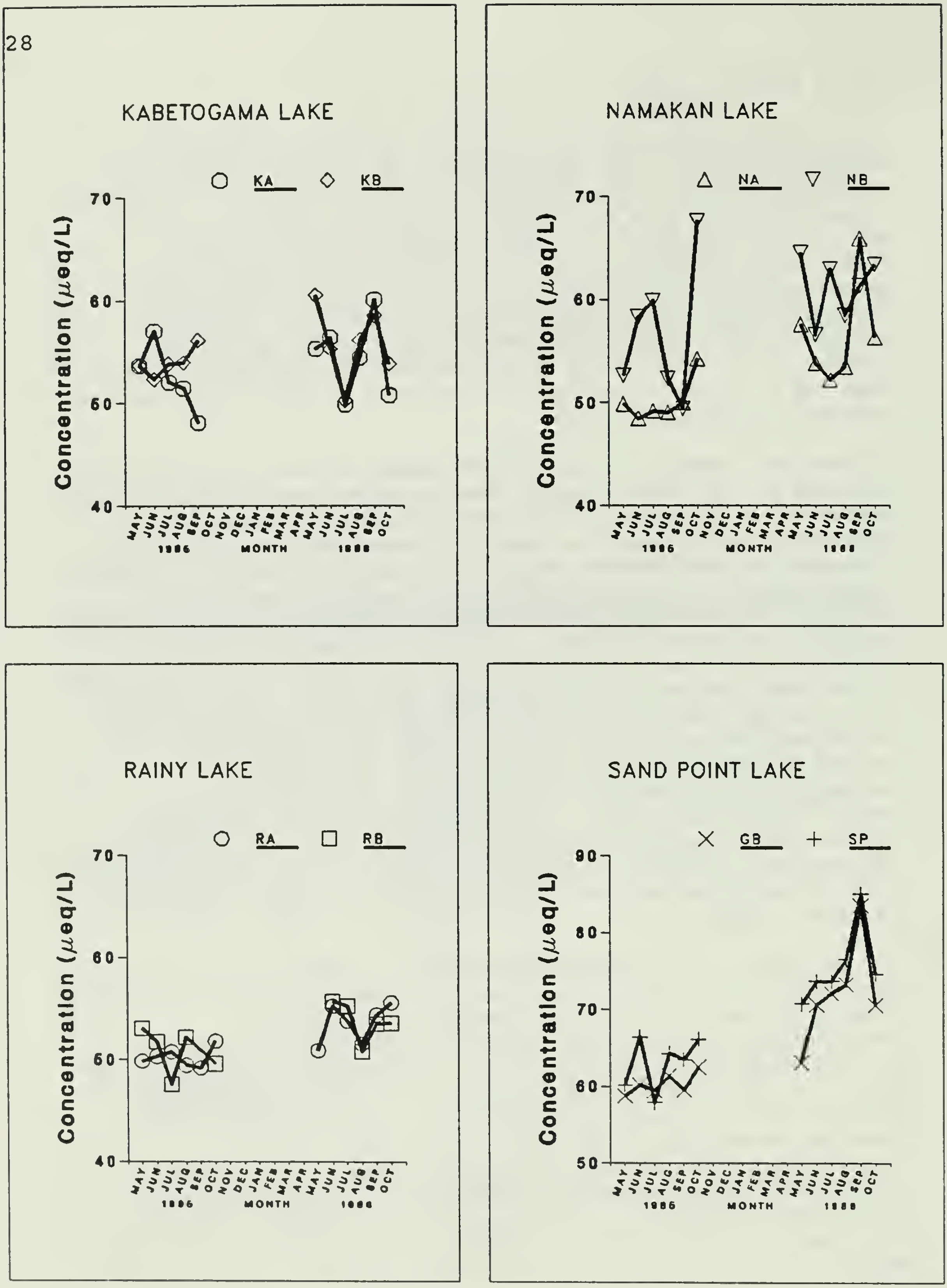


Figure 12. Mean sodium concentrations (μeq L^{-1}) for main lake stations (1, 3, and 10 m), Voyageurs National Park.

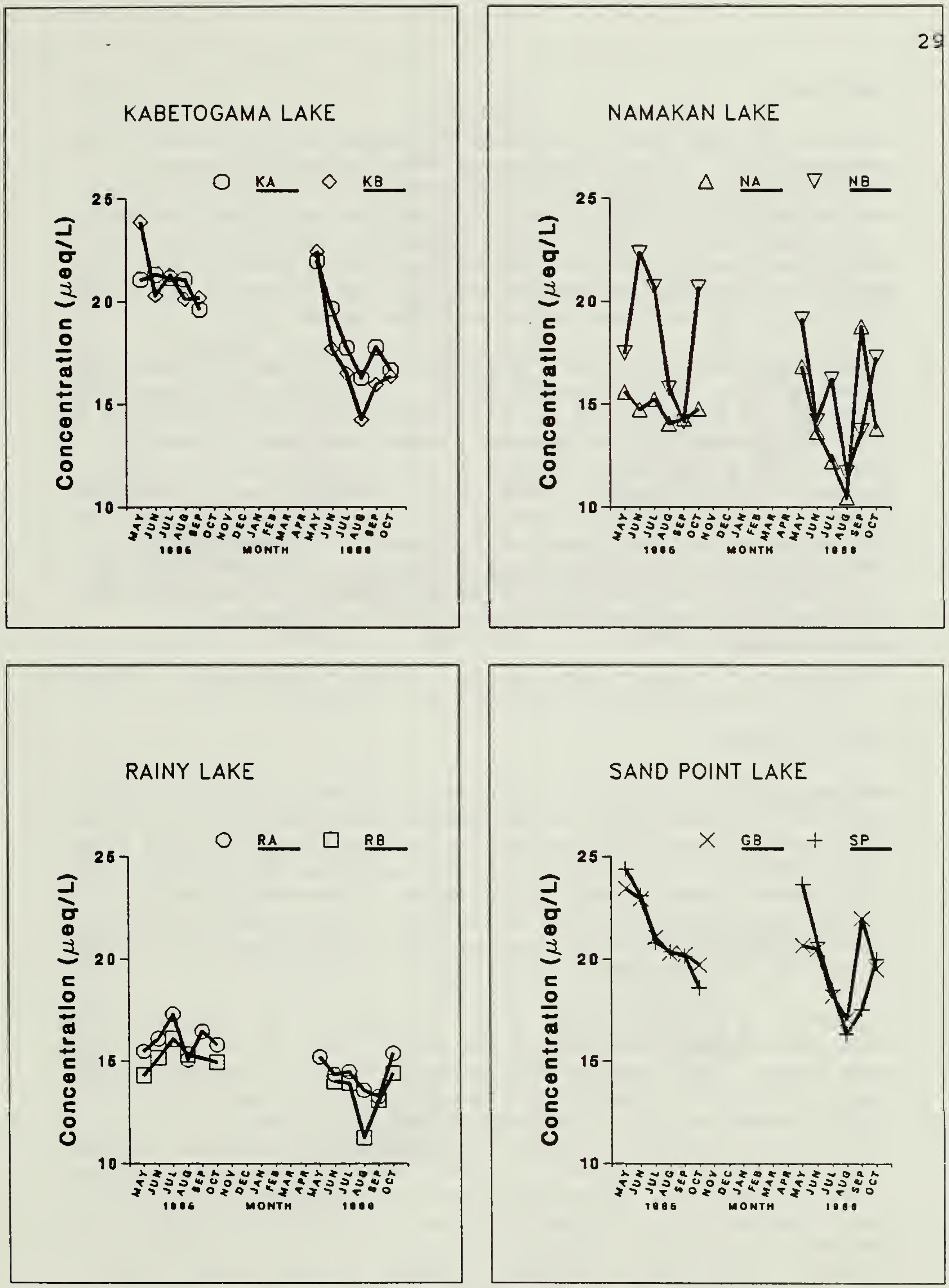


Figure 13. Mean potassium concentrations (μeq L^{-1}) for main lake stations (1, 3, and 10 m), Voyageurs National Park.

Ammonium:

Ammonia nitrogen (NH_3-N) in lakes is largely in the ionized (NH_4^+) ammonium form. In well-oxygenated waters ammonia-nitrogen concentrations are relatively low and highly variable spatially and seasonally. Analyses commonly show low concentrations of NH_3-N in oligotrophic waters, in the trophogenic zones of most lakes, and in most lakes after periods of circulation (Wetzel 1975). Highly variable NH_4^+ concentrations near the limits of detection (<2.0 μeq L^{-1}) were observed in the VOYA lakes.

A mean NH_4^+ concentration of 1.66 μeq L^{-1} (0.03 mg L^{-1}) has been found in Rainy Lake (Chevalier 1977). In this study a mean of 1.27 μeq L^{-1} was obtained for all samples taken at stations RA and RB. In Meadwood Bay, at nearshore sites less than 0.5 km from station KB, a mean concentration of NH_4^+-N for June, July and September was 9.97 μeq L^{-1} (NPS 1973). For all samples collected during the 1985 and 1986 sampling seasons at station KB, the mean concentration was much lower at 0.78 μeq L^{-1}. Mean NH_4^+ concentrations for the eight main sampling stations in 1985 and 1986 were 0.87 and 0.56 μeq L^{-1} respectively. Such concentrations are generally considered below the limits of accurate detectability.

Sum of Cations:

Kabetogama stations have the highest mean sum of cations (Ca^{+2}, Mg^{+2}, Na^+, K^+ plus NH_4^+) in all months except September 1985 when the concentration at KB appeared to be anomalously low (682.6 μeq L^{-1}). However, if the two previously mentioned KB-September 1985 outliers are deleted, this value becomes a reasonable 746.6 μeq L^{-1} (Fig. 14). Sum of cation values for all waters sampled ranged from 387.46 (KB, May 29 at 1 m) to 1491.23 (KF, Kettle Falls, May 30 at 1 m) with a mean of 781.18 μeq L^{-1} (n = 164).

Figure 14 is a mirror image of Ca^{+2} concentrations (Fig. 10) since this ion comprised over 60% of the total cation concentration in most cases. Also, mean monthly alkalinity values follow much the same pattern. Mean sum of cation concentrations (μeq L^{-1}) are highly correlated with alkalinities (as μeq L^{-1} HCO3-), R^2 = 0.913; $P < .001$ (Fig. 19), and with specific conductances (μmhos cm^{-1} @ 25° C.), R^2 = 0.892; $P < .001$ (Spearman rank correlation, n = 299), (Fig. 15). The correlation between specific conductance and the major cation nutrient species is usually quite high, as was the case for water samples collected during both field seasons. The increased "noise" at higher specific conductance values (Fig 15), is due to the presence of other ionic constituents which were not measured, and to the loss of linearity which occurs in the relationship between conductance and ion concentrations at higher levels.

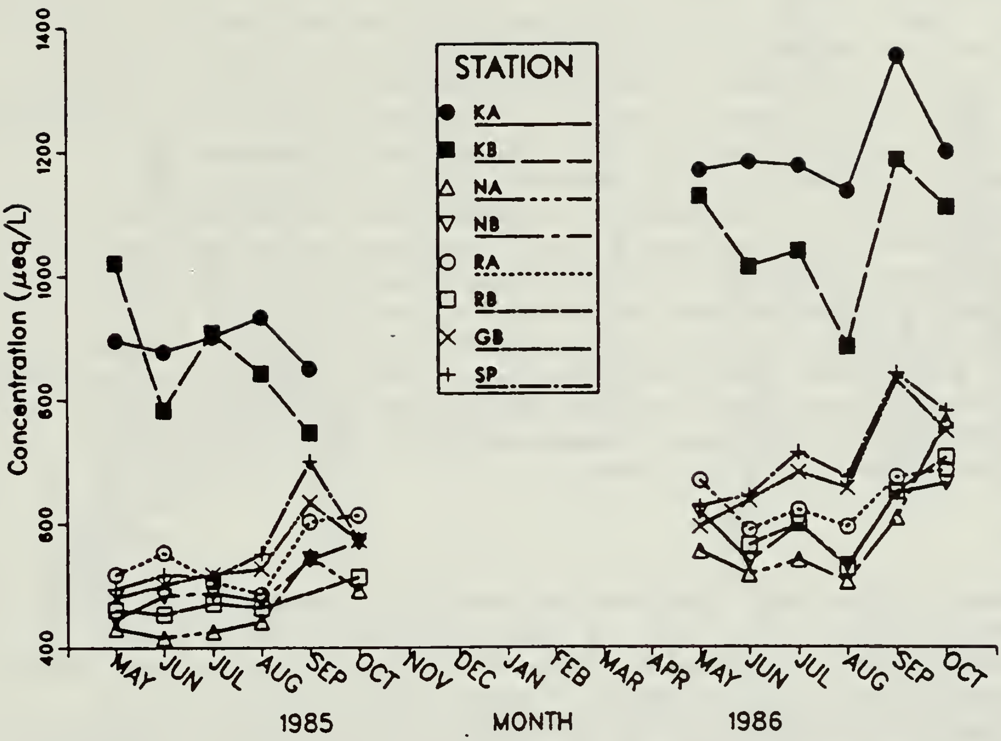


Figure 14. Mean sum of cation concentrations (μeq L^{-1}) for main lake stations (1, 3, and 10 m), Voyageurs Nat'l Park.

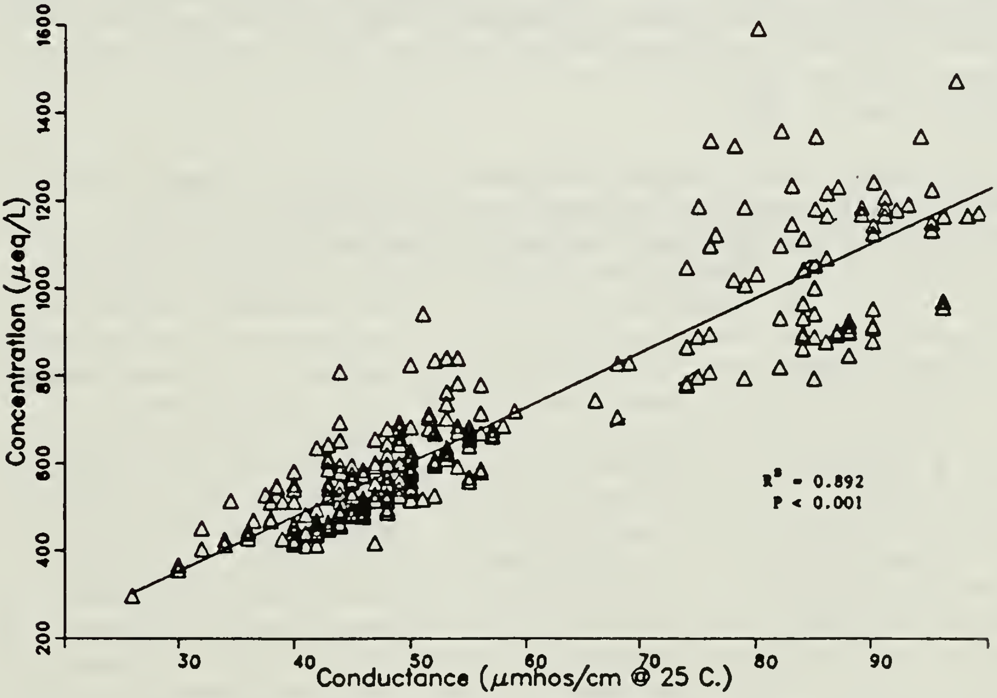


Figure 15. Relation between specific conductance and total cation concentration for 1, 3, and 10 m samples (n = 299).

In general, major cation concentrations are relatively low, with $Ca^{+2} > Mg^{+2} > Na^{+} > K^{+} > NH_4^{+}$ (on an equivalent basis). This pattern of dominant cations is characteristic of many inland Canadian Shield waters (Armstrong and Schindler 1971). High Ca^{+2} and Mg^{+2} with respect to Na^{+} and K^{+} typify inland Shield waters in well-scoured bedrock areas (Schindler and Nighswander 1970). Seasonal and particularly lake-to-lake variations in the distribution and abundance of both nutrient and major ions have been observed during this study. The seasonal patterns are likely to be chiefly a function of biological activity in the water column; internal sources of nutrients, ie. return of ions from sediments; and external sources of nutrients namely surface run-off, groundwater, and precipitation. Differences in ion chemistry observed between 1985 and 1986 at the same sites are attributed primarily to differences in precipitation amounts and runoff volumes between the two years.

pH:

Trends in pH at all stations are generally bimodal within the sampling season (Fig. 16). A drop in pH occurred in August, possibly due to increasing rates of detrital decomposition which accompany lake water warming. Primary production rates also increased in August. At all stations mean pH values then increase through September followed by sharp drops in October. Observed pH values are lower than those previously reported for June, July and September of 1973 (NPS 1973). The higher values of this previous study may be due to different sampling locations, but more likely to a general lack of understanding for problems associated with H^{+} measurement in dilute waters. Many of these earlier studies did not have external check samples as part of their quality assurance program, and the data sets often lack documentation (National Research Council 1986).

For comparison, mean values in standard units for Rainy Lake surface waters have been reported to range from 6.8 to 7.8 (Chevalier 1977) and from 6.8 to 8.8 (Hargis 1981). In this study, Rainy Lake pH's ranged from 6.23 to 7.13 (mean = 6.88, SD = 0.24, n = 120) for depths down to 10 m. One possible source of difference is that sampling sites for these earlier studies were at different locations. The highest pH values were in Kabetogama, and showed a sharp increase from June to July (approximately 5.5 to 7.2) in 1985. The greatest between-station variation in pH during a given month occurred in July 1985, when station KA had a mean value of 7.22 and GB was 6.45. The pH values for all waters sampled, including grab-samples at CR1, CR2, TC, LB, KF, BB, KN, ranged from 5.95 to 7.57, with a mean value of 6.70 (n = 260). Due to equipment problems, pH values for June, 1985 were taken from the biweekly data collected in Voyageurs National Park's limnological monitoring program (Larry Kallemeyn, NPS, Voyageurs National Park, unpublished data). Means and confidence limits of pH, alkalinity and specific conductance values at the eight primary sampling stations are provided below (Table 6).

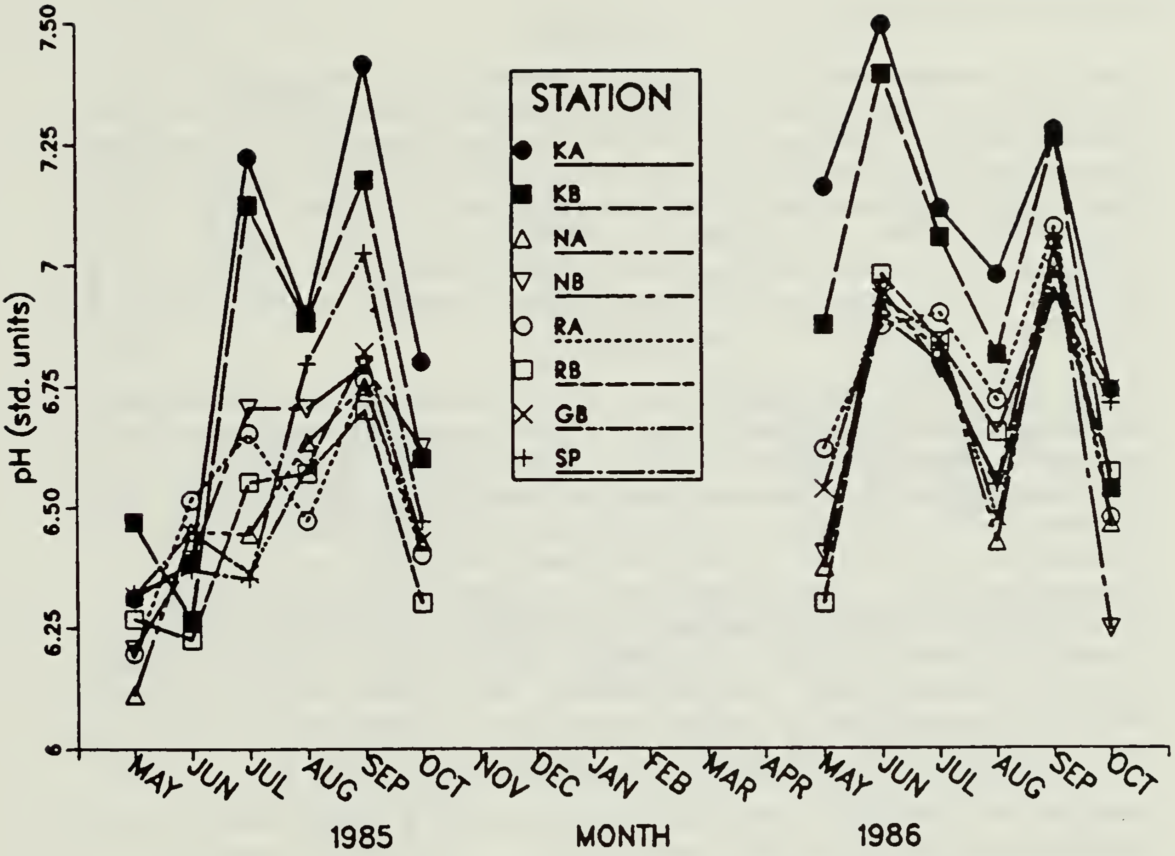


Figure 16. Mean pH in standard units for the main lake stations (1, 3, and 10 m), Voyageurs National Park.

Table 6. Means and confidence limits (a=.05) for pH, alkalinity (μeq L^{-1} HCO_3^-), and specific conductance (μmhos cm^{-1} @ 25° C.) at eight primary sampling stations during 1985 and 1986, Voyageurs National Park, MN.

STA.	n	pH*	alkalinity	conductance
KA	57	6.99±.10	515.9±35.8	88.02±1.16
KB	57	6.89±.09	446.7±27.6	78.93±2.14
NA	58	6.58±.07	181.9±12.6	43.48±0.88
NB	60	6.63±.07	188.8±13.1	46.66±1.24
RA	62	6.64±.06	245.0±12.0	50.07±0.89
RB	52	6.58±.07	198.1±14.4	43.48±0.93
GB	60	6.63±.06	223.5±15.9	49.37±1.00
SP	60	6.64±.07	226.0±18.4	51.20±1.00

*Confidence limits calculated directly from standard pH units.

Specific Conductance:

Specific conductance is a reliable estimator of the total concentration of dissolved cations in lake waters, which, within a certain range of values, can reflect water fertility. Kabetogama Lake is markedly different from the other study lakes (Fig. 17). Mean specific conductance for the eight main stations ranged from 37 (RB Oct., 1985) to 97 μmhos cm^{-1} (KA May, 1986). Mean conductance for the eight main stations was 54.3 in 1985 and 58.3 in 1986. The range for all water samples collected was from 30 to 103, with a mean of 57.3 μmhos cm^{-1}.

In general, specific conductance values are comparable to those observed at shallow-water sites in the summer 1973 Resources Basic Inventory (RBI) study (NPS 1973). Lakes in the ELA of northwestern Ontario display similar ranges in conductivity (20 to 55 μmhos cm^{-1}, Schindler and Nighswander 1970). Mean specific conductance values for Rainy Lake have been reported at 44 (Chevalier 1977) and 60 μmhos cm^{-1} (taken as the mean at one station located midway between RA and RB at 1 m below surface, thermocline and 1 m above sediments, during June, July and August of 1979, Hargis 1981). In this study, mean conductances for Rainy Lake are comparable and range from 43 to 59 μmhos cm^{-1} (1-10 m depth, mean = 50.3, SD = 3.9, n = 120).

Changes in specific conductance are directly proportional to ionic concentrations (Otsuki and Wetzel 1974). Therefore, specific conductance should be well-correlated with concentrations of dominant ionic constituents, (see Sum of Cations). Mean conductance (1, 3 and 10 m by date) plotted over mean alkalinity indicates some between-lake differences (Fig. 18). Kabetogama Lake waters are distinctive in their higher mean specific conductances and alkalinities. The cluster of Kabetogama points having higher alkalinity relative to specific conductance is for the 1986 season. The difference between 1985 and 1986 data is especially noticeable in Kabetogama, but can also be seen in the mean values for the other lakes. Combining 1985 and 1986 data for the eight main sampling stations, alkalinity (μeq L^{-1} $HCO3^{-}$) was strongly correlated with specific conductance (μmhos cm^{-1} @ 25° C.), $R^2 = .852$, $P < .001$, $n = 466$.

Alkalinity:

Alkalinity, expressed here (Table 6) as bicarbonate (HCO_3^-), is an indicator of acid buffering capacity. Voyageurs lakes have relatively low alkalinities for natural waters, which usually range from 330 to 3300 μeq L^{-1} HCO_3^- (Lind 1979). As with pH, the highest alkalinities were consistently observed in Kabetogama Lake (Figs. 18 and 19, Table 6). In 1985 mean alkalinities for the upper ten meters ranged from 124.6 (GB July) to 451.0 (KA Sept.), while in 1986 alkalinities were as high as 679.0 (KA May).

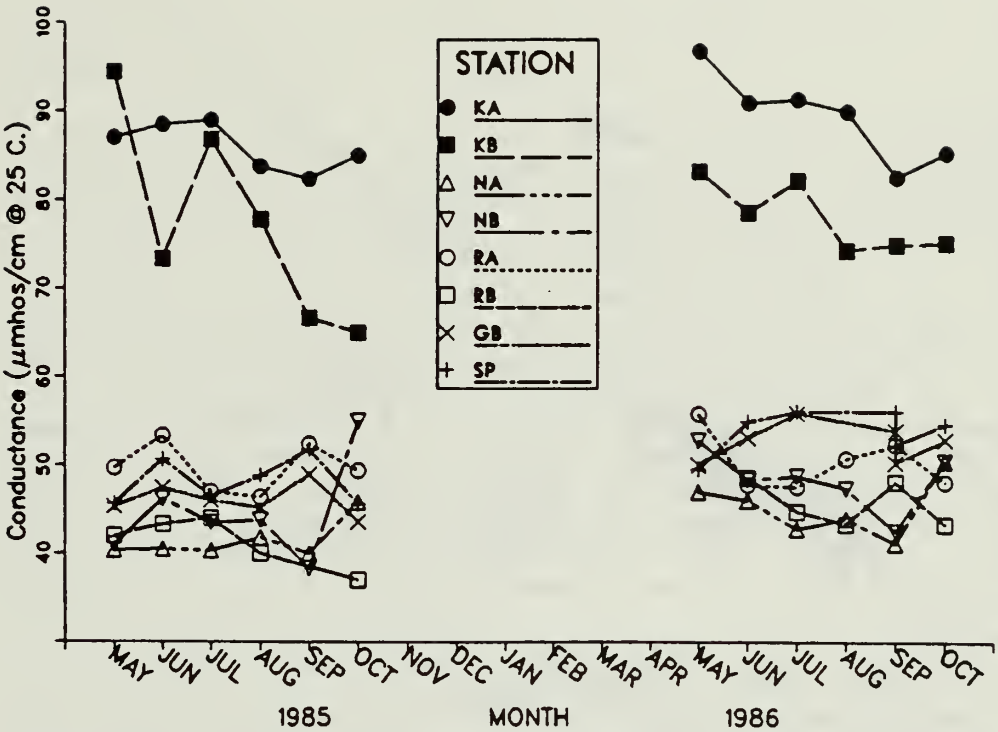


Figure 17. Mean specific conductance (μmhos cm^{-1} @ 25° C.) for the main lake stations (1, 3, and 10 m), Voyageurs National Park.

Namakan Lake stations showed mean epilimnion alkalinities below 165 over the entire 1985 sampling period, while values for GB and SP were intermediate between those for Kabetogama and those for Namakan. As with conductance and the sum of cations, alkalinity values for the west Rainy station (RA) were almost always higher than those for east Rainy (RB) during both years. In riverine lakes, as in most lotic systems, "downstream" (RA) sites usually yield higher alkalinity and specific conductance values than "upstream" (RB) sites. The alkalinity values for all waters sampled ranged from 65.6 to 754.4, with a mean of 285.4 μeq L^{-1} (n = 518).

An earlier study reports total alkalinity for Rainy Lake as being 410 μeq L^{-1} (Chevalier 1977), however the value of 255.8 μeq L^{-1} (taken as a mean at three stations over June, July and August 1979, Hargis 1981) agrees more closely with the current study (referenced alkalinities have been converted from mg L^{-1} $CaCO_3$ to μeq L^{-1} HCO_3^-). Rainy Lake alkalinities in the 1985 and 1986 sampling seasons at five depths, two stations, yielded a mean value of 224.7 μeq L^{-1} (range = 115-328, SD = 70.5, n = 120). Mean alkalinity for the eight main sampling stations was 209.9 in 1985 and 342.8 μeq L^{-1} in 1986. The significantly higher alkalinities obtained in 1986, particularly prominent at the Kabetogama Lake stations, are most likely the result of reductions in runoff and direct precipitation during that year.

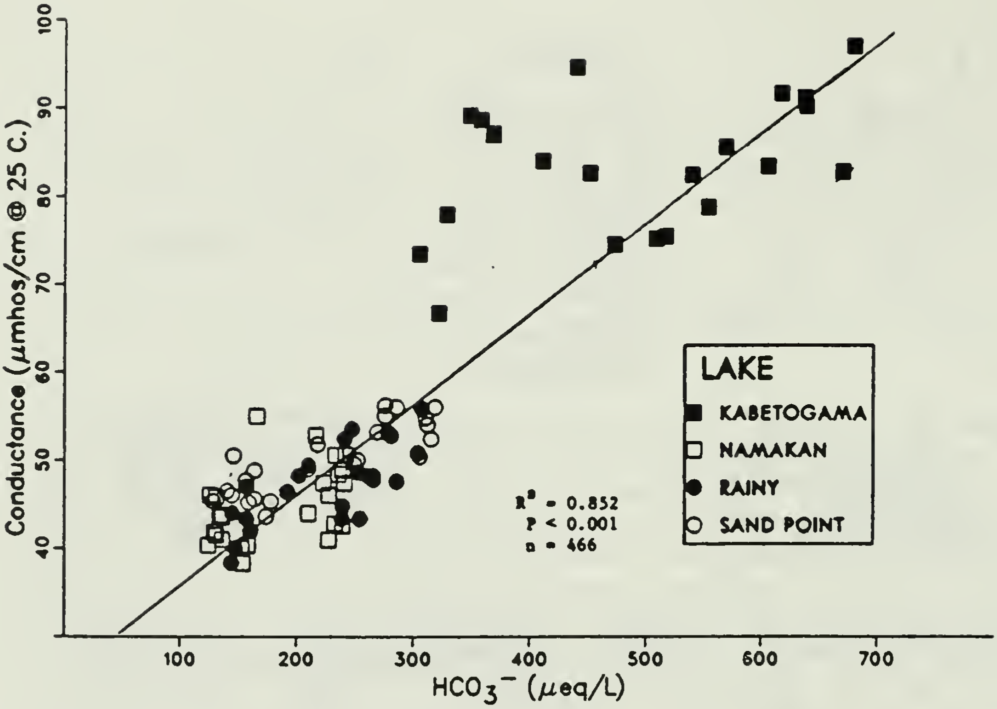


Figure 18. Relation between mean specific conductance and bicarbonate alkalinity (1, 3, and 10 m), for the four study lakes, Voyageurs National Park.

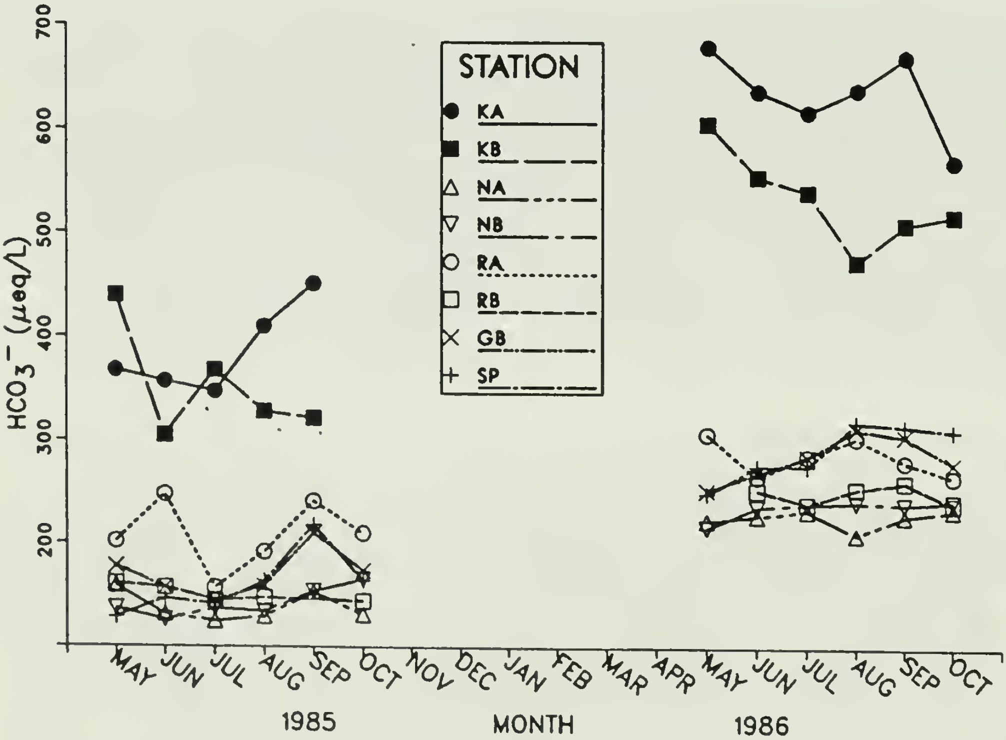


Figure 19. Mean alkalinities (μeq L^{-1} HCO_3^-) for the main lake stations (1, 3, and 10 m) Voyageurs National Park.

Nitrate:

Nitrate nitrogen (NO_3^-) is the most abundant form of inorganic-N in Voyageurs lake waters, with mean concentrations at the eight primary stations ranging from undetectable levels, < 0.16 μeq L^{-1} (< 0.01 mg L^{-1}) at KB in September of 1985 and 1986, to 7.42 μeq L^{-1} (0.46 mg L^{-1}) at station NB in October 1985 and May 1986. As with SO_4^{-2}, stations KA and KB had consistently lower concentrations with mean values never > 2.4 μeq L^{-1}, although levels in October 1985 might have surpassed this (Fig. 20). Positive NO_3^- gradients have been observed from upstream to downstream stations and is an expected situation in a connected reservoir system (Cabecadas and Brogueira 1987). The mean NO_3^- concentration for all waters sampled, including grab-samples, was 2.47 μeq L^{-1} (0.15 mg L^{-1}). These NO_3^- levels are comparable to those reported in the literature for Rainy Lake, 3.0 μeq L^{-1} (Chevalier, 1977), and for nine lakes in southern Quebec, 2.09 μeq L^{-1} (Kalff and Bentzen 1984).

A seasonal trend in mean NO_3^- concentrations seems apparent for all of the primary sampling stations. Nitrate concentrations (1, 3, and 10 m) increased between May and June as lake inputs from runoff increased and the lakes became more mixed. Lower June concentrations in 1986 probably reflect lesser inputs from runoff and direct precipitation than in 1985 (Fig. 5). Concentrations at all stations then decreased by roughly 1.0 μeq L^{-1} in July, perhaps reflecting utilization of major quantities during summer algal growth. This reduction to less than detectable levels at some stations is also common in the ELA (Armstrong and Schindler 1971). During the period when concentrations approached undetectable levels, (particularly at the Kabetogama stations), blue-green algal numbers appeared to reach their maximum (late August). Since these are N-fixers this may be indicative of an algal reliance on molecular N_2 during these high productivity periods. Nitrate levels then increase sharply to higher values in October, as water temperatures and algal biomass decreased and high runoff episodes occurred. Again, concentrations for October 1985 at stations KA and KB are not available, but are also expected to have increased between September and October.

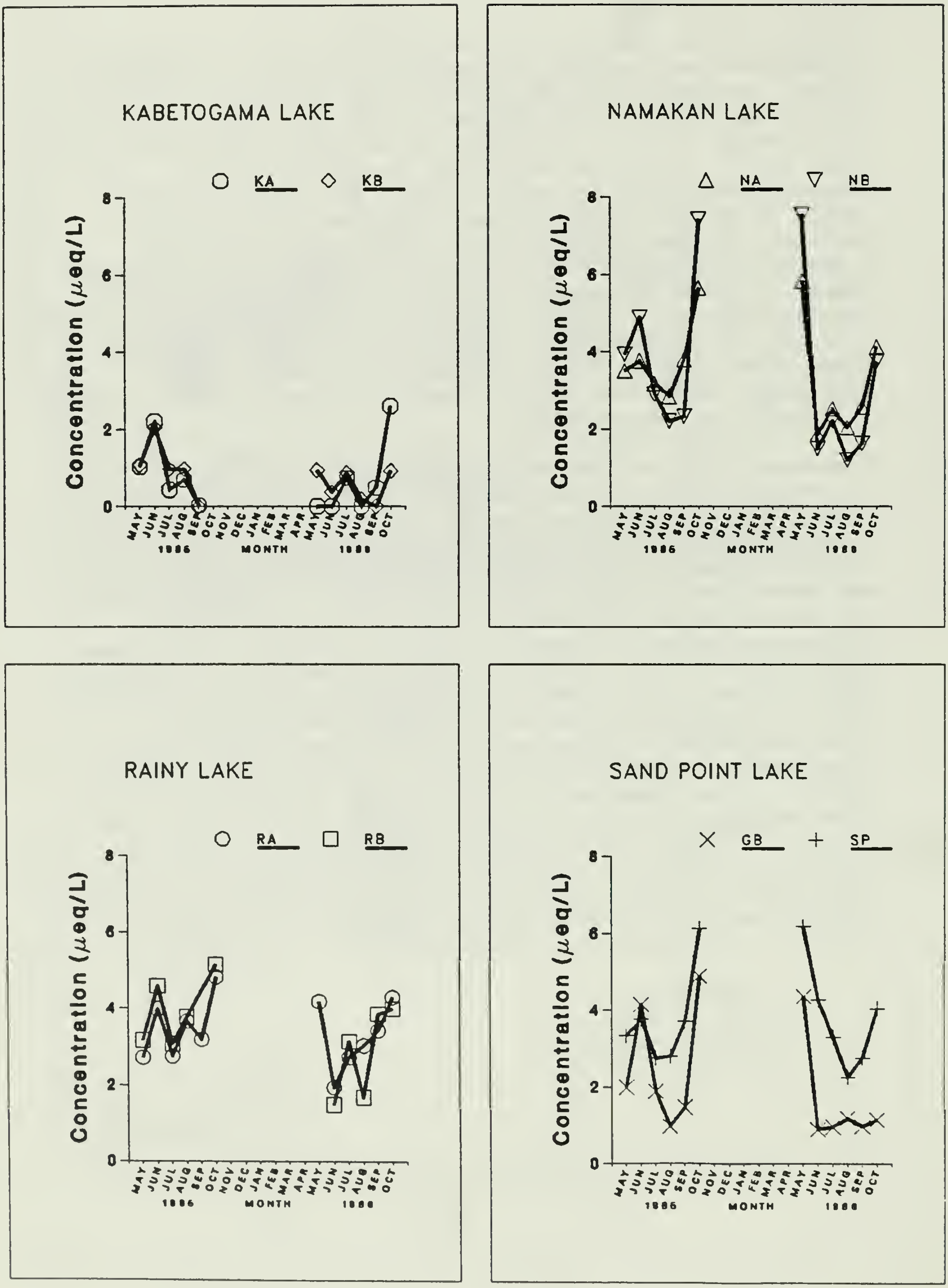


Figure 20. Mean nitrate concentrations (μeq L^{-1}) for the main lake stations (1, 3, and 10 m), Voyageurs Nat'l Park.

Total Kjeldahl Nitrogen:

In 1986, total kjeldahl nitrogen (TKN) ranged from .22 to .83 mg L^{-1} for all waters analyzed (mean = .46, SD = .11, n = 92). In less-dilute prairie saline lakes, summer TKN ranged from 1.09 to 10.74 mg L^{-1} (Bierhuizen and Prepas 1985). Total kjeldahl nitrogen for Rainy Lake is reported as 0.40 mg L^{-1} (Chevalier 1977), comparing closely to a summer mean of 0.36 mg L^{-1} obtained in this study. The total kjeldahl nitrogen values are also comparable with those obtained in the 1973 RBI study (NPS 1973), though generally lower. Values reported in 1973 are higher because samples were collected at productive shallow-water sites such as Meadwood, Sullivan and Black Bays during June, July and September only. The highest mean TKN values observed in 1986 were also at the shallower grab-sample sites; Tom Cod (TC), Lost (LB), Black (BB) and Cranberry (CR1 and CR2) Bays, in order of decreasing mean summer TKN values.

Inter-station differences in TKN's can also be seen (Fig. 21). Except for the Kabetogama stations, the shallower grab-sample sites almost always had higher TKN concentrations. Concentrations at Tom Cod (a bay in west Kabetogama) paralleled those at the open-water KA site, but were 0.1-0.2 ppm higher except in May. Samples for TKN and total non-purgeable organic carbon (TOC) were collected most frequently at the east Kabetogama (KB) station. Total kjeldahl nitrogen at KB decreased sharply in early June to the lowest concentration observed at any station throughout the sampling season (.22 mg L^{-1}) and then increased from early July until the end of August. Following the late August TKN peak, there was a general decline until the beginning of October when concentrations leveled off at roughly .40 mg L^{-1} and remained stable through late November.

Combining all stations, significant positive correlations were found between TKN and volumetric C-assimilation rates ($R^2 = .469$, $P < .002$, $n = 46$), and between TKN and chlorophyll-a concentrations ($R^2 = .328$, $P < .05$, $n = 50$). As TKN was negatively correlated with NO_3^- ($R^2 = -.489$, $P < .001$, $n = 50$) and NH_4^+ ($R^2 = -.199$, $P < .05$, $n = 70$), and NO_2^{-2} was undetectable in 166 samples, another form of nitrogen must be responsible for the positive correlation between TKN and both C-assimilation rates and chlorophyll-a concentrations. Considering the summer blooms of N-fixing phytoplankton it is likely that atmospheric N_2 provides a major source of utilizable N, particularly during the maximum biomass months from June through September.

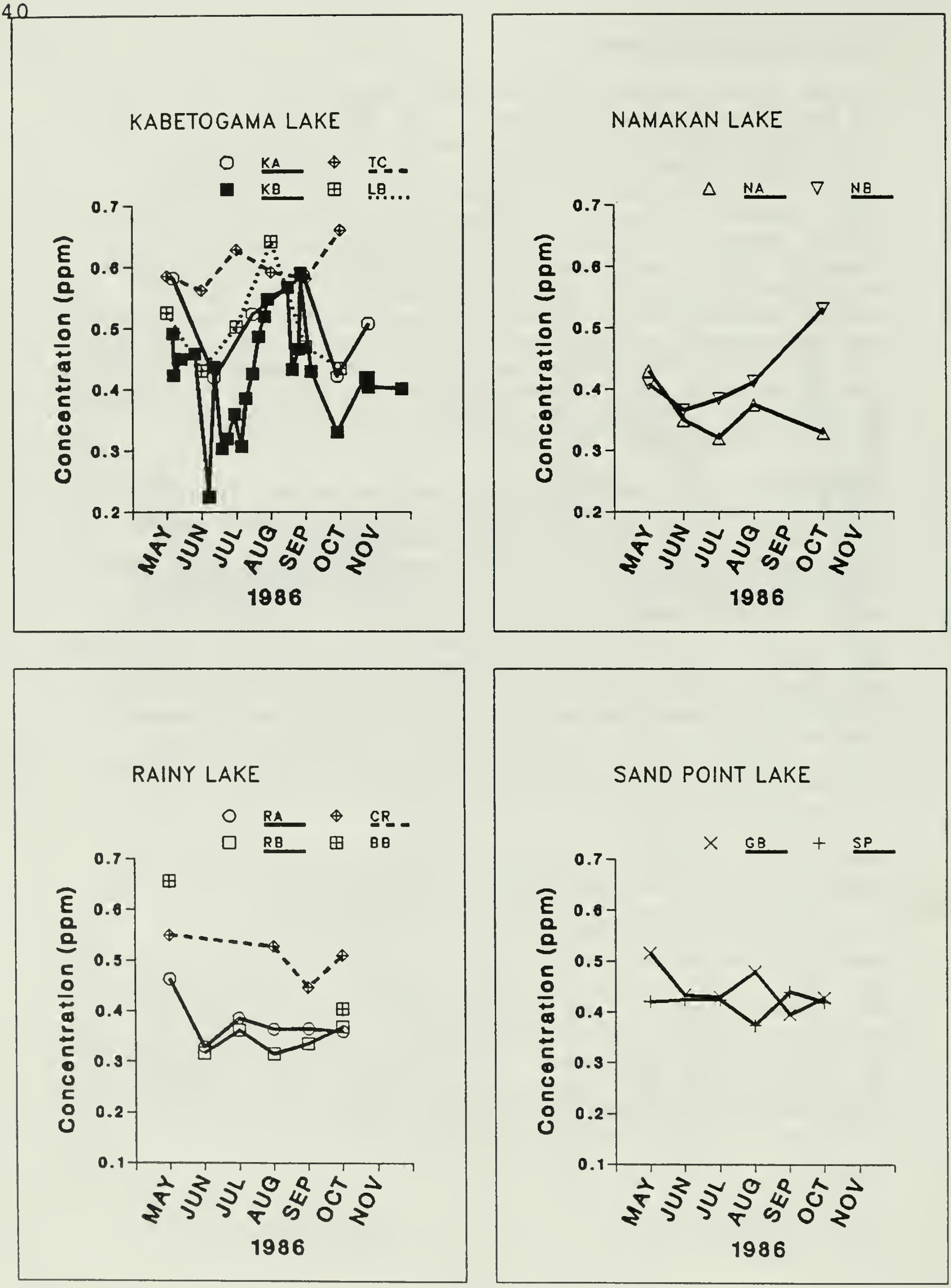


Figure 21. Total Kjeldahl Nitrogen (ppm) at 1 m for main lake stations and four grab-sample sites during 1986, Voyageurs National Park, MN.

Phosphate:

Ortho-phosphate (PO_4^{-3}) data are not presented since nearly all sample concentrations were below levels of detection (20 $\mu g\ L^{-1}$, or ppb). In general, PO_4^{-3} comprises only 5 to 10% of total phosphorus in lakes, and low levels of this essential nutrient are not unexpected. Only 10 of 300 samples contained detectable PO_4^{-3} concentrations, and sample contamination seems likely in a few of these cases. In the ELA, dissolved PO_4^{-3} was usually not detectable in summer either, being < 1 $\mu g\ L^{-1}$, except infrequently in hypolimnetic waters (Armstrong and Schindler 1971). Phosphate, because of its high turnover (Rigler 1964) is generally meaningless as a measure of phosphorus availability to phytoplankton (Schindler and Nighswander 1970). It is much more relevant to the question of algal productivity to view the phosphorus concentrations in terms of total phosphorus, since most of the phosphorus is bound in the particulate component at any given time.

Total Phosphorus:

Total phosphorus (TP) data has not been directly obtained in this study, as a good standard curve could not be arrived at within the expected concentration range (approximately 1 to 100 $\mu g\ L^{-1}$). However, based upon nitrogen concentrations in Kabetogama and the 13:1 N:P ratio cited for this lake (Hargis 1981), 1986 summer TP's probably ranged from roughly 17 to 45 $\mu g\ L^{-1}$, with an approximate mean of 33 $\mu g\ L^{-1}$ in Kabetogama Lake. Summer 1973 TP in Kabetogama's Meadwood Bay ranged from 20 to 100 $\mu g\ L^{-1}$, with a mean for June, July and September of 48.7 $\mu g\ L^{-1}$ (NPS 1973). A slightly lower TP value (27 $\mu g\ L^{-1}$) has been reported for the less-productive Rainy Lake (Chevalier 1977).

Total phosphorus values derived from several empirical relationships to chlorophyll-a concentrations (Dillon and Rigler 1974, Prepas and Trew 1983, and Ostrofsky and Rigler 1987) overestimated those predicted on the basis of N:P ratios. The closest approximation of TP concentrations based on N:P ratios was derived by calculating chlorophyll-based trophic state indices (TSI's, see page 52) and then back-calculating TP according to the TP-based TSI relationship (Carlson 1977). In Kabetogama Lake TSI-based TP concentrations ranged from 12.2 to 63.1 with a mean of 28.0 $\mu g\ L^{-1}$, comparable to those obtained based on the 13:1 N:P ratio. Combining chlorophyll-a concentrations with those from a previous study (Hargis 1981) yielded a summer mean TSI-derived TP concentration of roughly 30 $\mu g\ L^{-1}$ for Kabetogama Lake. This figure was chosen as the initial TP concentration in the TP modeling exercise (Appendix G).

The empirical relationships linking TP to chlorophyll-a concentrations may not be useful in these lakes on anything less than an annual basis. It is likely that the VOYA lakes, particularly Kabetogama, do not have N:P ratios high enough to ensure an adequate supply of nitrogen throughout the summer. For instance, TKN:TP ratios for the 19 southern Ontario lakes used in obtaining Dillon and Rigler's phosphorus-chlorophyll relationship ranged from 15.0 to 44.5 (mean = 29.3) (Dillon and Rigler 1974), well above the ratio of 13 cited for Kabetogama Lake (Hargis 1981).

A definite point at which nitrogen becomes limiting in relation to phosphorus has not been determined. It has been reported that N-fixation begins at N:P ratios < 5 (Schindler 1975). It has been found that N-fixing cyanobacteria were associated only with those ELA lakes with TN:TP loading ratios < 10 (Flett et al. 1980). Other data indicates N-limitation in lakes with TN:TP ratios < 13 (Ryding 1980), while some have seen that lakes with TN:TP ratios which are < 29 tend to support blue-green, N-fixing algae (Smith 1983). The TN:TP ratios in the VOYA lakes undoubtedly fluctuate seasonally around the threshold area between which either one or the other of these nutrients may be limiting.

Sulfate:

The dominant form of sulfur in water is found in the oxidized state (SO_4^{-2}). Through 1985, mean sulfate concentration (μeq L^{-1}) for the eight primary sampling stations ranged from 33.9 (KB Sept.) to 90.1 (NB May). This is equal to a range of 1.63 to 4.42 mg L^{-1}. Observed SO_4^{-2} concentrations in ELA lakes range from 0.6 to 5.0 mg L^{-1} (Armstrong and Schindler 1971). A mean for Rainy Lake has been reported as 8.0 mg L^{-1} (Chevalier 1977), while mean Rainy Lake concentration in this study was roughly 3.4 mg L^{-1}. Different methodologies may account for such a discrepancy.

Sulfate concentrations were fairly consistent on a monthly basis with variation usually less than 10 μeq L^{-1}, (Fig. 22). Exceptions to this were in September 1985, when sharp drops in SO_4^{-2} were obtained at station KA. Similar drops occurred between September and October of 1986 at the Kabetogama stations. These decreases are possibly due to reduction of SO_4^{-2} to H_2S with increasing decomposition in marsh and shallow-water sediments, coupled with reduced total inputs. Mean SO_4^{-2} concentrations were consistently lower in Kabetogama waters during each sampling month of the study. October data for KA and KB are unavailable due to sample loss.

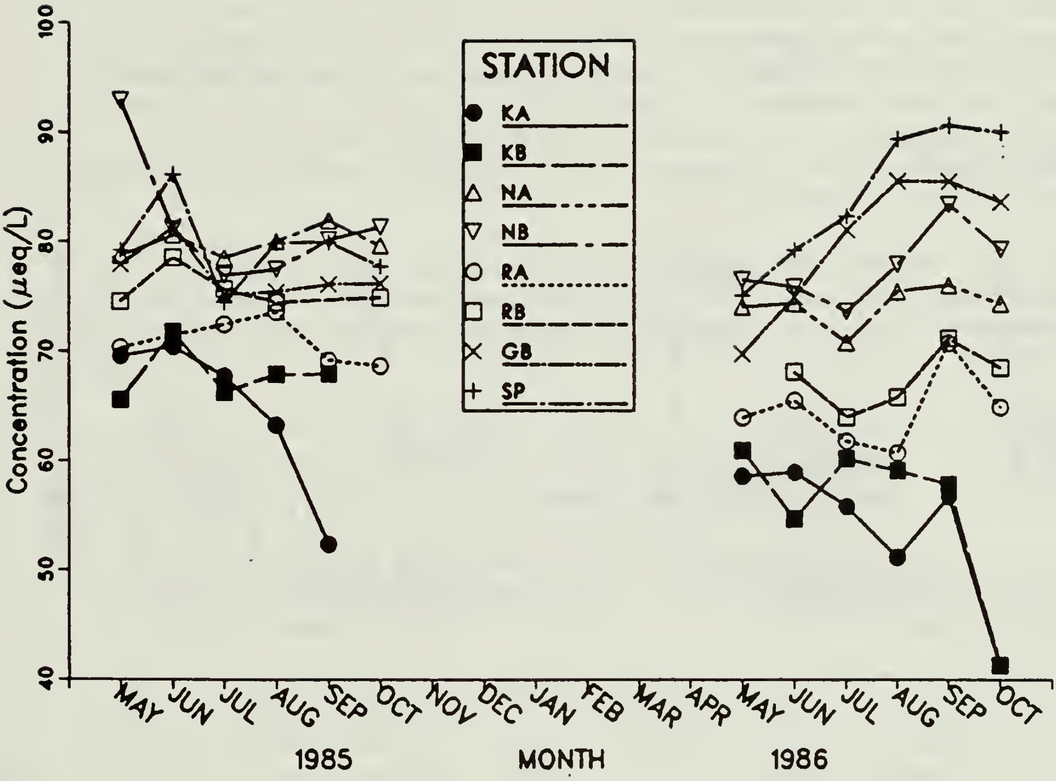


Figure 22. Mean sulfate concentrations (µeq L^{-1}) for the main lake stations (1, 3, and 10 m), Voyageurs Nat'l Park.

Chloride:

Chloride is usually not a dominant anion in open lake waters. Pollution sources of chloride (Cl^-) can modify natural concentrations greatly. For example, Cl^- concentrations in Lake Erie tripled in just 50 years due largely to increased inputs from industrial sources, municipal waste and road salting (Ownbey and Kee 1967). The Cl^- pulse observed in June of 1985 at station KA (Kepner and Stottlemyer 1986), was not present in 1986. It is now suggested that Voyageurs' Cl^- concentrations are relatively stable from May through October at all stations (Fig. 23). Although station KA is located adjacent to a more developed stretch of shoreline, the jump in mean Cl^- concentration in June, 1985 has been attributed to probable incomplete rinsing of two acid-washed (HCl) sample bottles, and not to pollution inputs from surrounding resorts and seasonal cottages. The high Cl^- concentrations in May, 1986 (particularly at SP) probably reflect winter levels which occur before dilution by high runoff events. Consistent seasonal trends are not evident in concentrations of this conservative ion since concentrations are not much influenced by metabolic utilization.

Armstrong and Schindler (1971) report a mean Cl^- concentration of 39.5 μeq L^{-1} for the euphotic zones of seven ELA lakes, while Clear Lake in eastern Ontario had May levels of 28 μeq L^{-1} (Schindler and Nighswander 1970). This Clear Lake value is consistent with concentrations observed at the eight main VOYA lake stations (mean = 25.7 μeq L^{-1}). Average concentrations of Cl^- in natural fresh waters are approximately 234 μeq L^{-1} (Livingstone 1963, in Wetzel 1975), roughly ten-fold greater than those found in this study.

The mean values and standard deviations of the major ion concentrations (μeq L^{-1}) for all waters sampled at each of the eight main stations throughout the entire study are supplied below in Table 7.

Table 7. Means and standard deviations of ionic concentrations (µeq L^{-1}), pH (std. units) and specific conductance (µmhos cm^{-1} @ 25° C) for the eight primary sampling stations over the 1985 and 1986 sampling seasons.

	KA	KB	NA	NB	RA	RB	GB	SP
pH	6.99 (0.38)	6.89 (0.35)	6.58 (0.25)	6.63 (0.26)	6.64 (0.24)	6.58 (0.27)	6.63 (0.23)	6.64 (0.25)
HCO_3^-	515.94 (134.81)	446.74 (104.14)	181.88 (48.05)	188.76 (50.51)	245.02 (47.40)	198.11 (51.66)	223.53 (61.83)	225.99 (71.34)
Ca^{+2}	519.36 (111.06)	467.32 (103.17)	260.04 (84.12	268.12 (44.54)	301.55 (46.75)	275.37 (70.03)	294.19 (62.14)	308.60 (66.03)
Mg^{+2}	447.22 (59.41)	387.81 (99.03)	181.20 (19.70	199.16 (22.84)	214.05 (25.63)	183.89 (18.64)	221.07 (33.95)	226.21 (34.31)
Na^+	53.28 (3.99)	52.12 (11.00)	52.94 (5.11	58.75 (6.85)	51.51 (2.52	52.32 (2.94)	65.12 (7.10)	68.53 (7.51)
K^+	19.73 (2.03)	18.40 (4.75)	14.56 (2.51)	17.18 (3.86)	15.35 (1.25)	14.40 (1.28)	20.66 (1.71)	20.57 (2.58)
NH_4^+	0.52 (1.29)	0.78 (1.29)	0.97 (1.05)	0.97 (1.16)	0.67 (0.98)	0.66 (1.00)	0.74 (0.90)	0.53 (0.99)
NO_3^-	0.74 (0.92)	0.79 (0.66)	3.51 (1.31)	3.57 (2.18)	3.37 (0.91)	3.39 (1.15)	2.19 (1.56)	3.84 (1.93)
PO_4^{-3}	0.00 (0.00)	0.02 (0.12)	0.00 (0.00)	0.00 (0.02)	0.06 (0.24)	0.01 (0.06)	0.01 (0.04)	0.01 (0.08)
SO_4^{-2}	59.65 (8.54)	59.11 (13.59)	75.21 (10.58)	79.70 (8.01)	68.21 (4.11)	72.12 (4.95)	77.77 (4.56)	81.31 (5.46)
Cl^-	27.80 (18.29)	22.92 (8.36)	22.39 (7.23)	26.60 (9.23)	21.21 (2.48)	20.24 (2.18)	30.01 (6.85)	40.01 (9.56)
Sum-cats	1386.35 (239.44)	1237.97 (269.95)	683.06 (155.25)	726.05 (101.49)	784.16 (98.46)	710.22 (130.18)	797.90 (141.08)	830.16 (147.27)
Cond.	88.02 (4.36)	78.93 (8.09)	43.60 (3.39	46.64 (4.80)	50.01 (3.38)	43.62 (3.09)	49.40 (3.86)	51.15 (3.88)

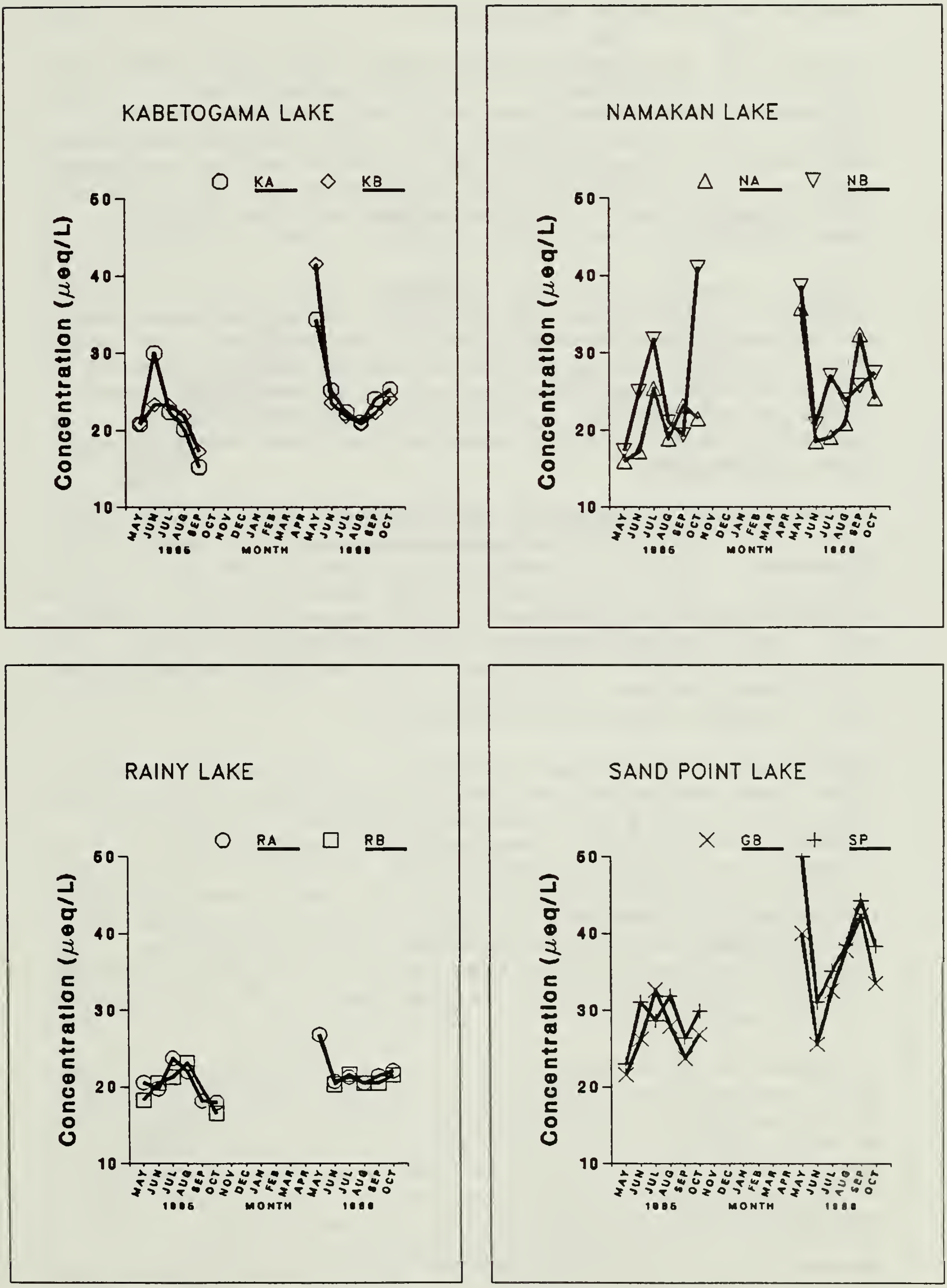


Figure 23. Mean chloride concentrations (μeq L^{-1}) for the main lake stations (1, 3, and 10 m), Voyageurs Nat'l Park.

Chemical Relationships Among Lakes:

On nearly all sampling dates, Kabetogama stations had higher mean HCO_3^- as well as combined Ca^{+2} and Mg^{+2} concentrations. Bicarbonate alone however does not balance these two dominant cations in any of the VOYA lakes (Fig. 24). The imbalance between HCO_3^- and the two dominant cations is greatest at the Kabetogama stations. It is likely that the imbalance is made up of organic acids. Tannic, humic and yellow organic acids are largely responsible for the "tea-like" coloration of VOYA lake waters.

Sulfate is apparently of less importance relative to anions other than HCO_3^- in Kabetogama Lake (Fig. 25). Kabetogama again shows the increasing importance of organic acids relative to the other lakes. Although organic acid concentrations were not examined in this study their importance, particularly in shallow Kabetogama Lake is strongly implied. Also note the generally higher variability in dominant ion concentrations found throughout the study in Kabetogama.

A strong linear relationship exists between the mean HCO_3^-/SO_4^{-2} ratio and mean HCO_3^- concentrations for all lakes except Kabetogama. At HCO_3^- concentrations greater than approximately 400 μeq L^{-1}, this relationship breaks down (Fig. 26). For the Kabetogama stations decreases in SO_4^{-2} concentrations relative to HCO_3^- result in the inflection point followed by a steeper curve for these stations. During months of low HCO_3^- concentrations, SO_4^{-2} almost becomes the dominant anion. This was particularly true at Namakan Lake stations during 1985.

Magnesium is relatively more important in Kabetogama than in the other lakes, particularly at the mid-range of HCO_3^- concentrations (Fig. 27). However, it is unusual for Ca^{+2}/Mg^{+2} ratios to approach a value of 1.0. Considering the observed HCO_3^- concentrations and geology it is likely that Mg^{+2} concentrations are largely the result of bedrock inputs. On the west side of Kabetogama Lake, headlands are formed by granite and pegmatite, while the small bays and indentations are underlain by the magnesium-containing biotite schist $Mg_6(Si,Al)_8O_{20}(OH)_4$ (Zumberge 1952) which may contribute to somewhat higher Mg^{+2} concentrations in this lake.

In general, a trend towards reduced pH values is often seen with HCO_3^- concentrations < 200 μeq L^{-1}. However, this can be seen clearly only for station SP (Fig. 28). The VOYA lakes appear to be well-buffered at this time. Seasonal variation in HCO_3^- was much less than year to year (1985-1986) variation and appears to be related to total precipitation inputs. There is also little seasonal variation in acid (H^+) input concentrations in precipitation and particularly in stream runoff (Table 5). However, the susceptibility of these lakes to impacts from acidic atmospheric deposition remains outside the scope of this study.

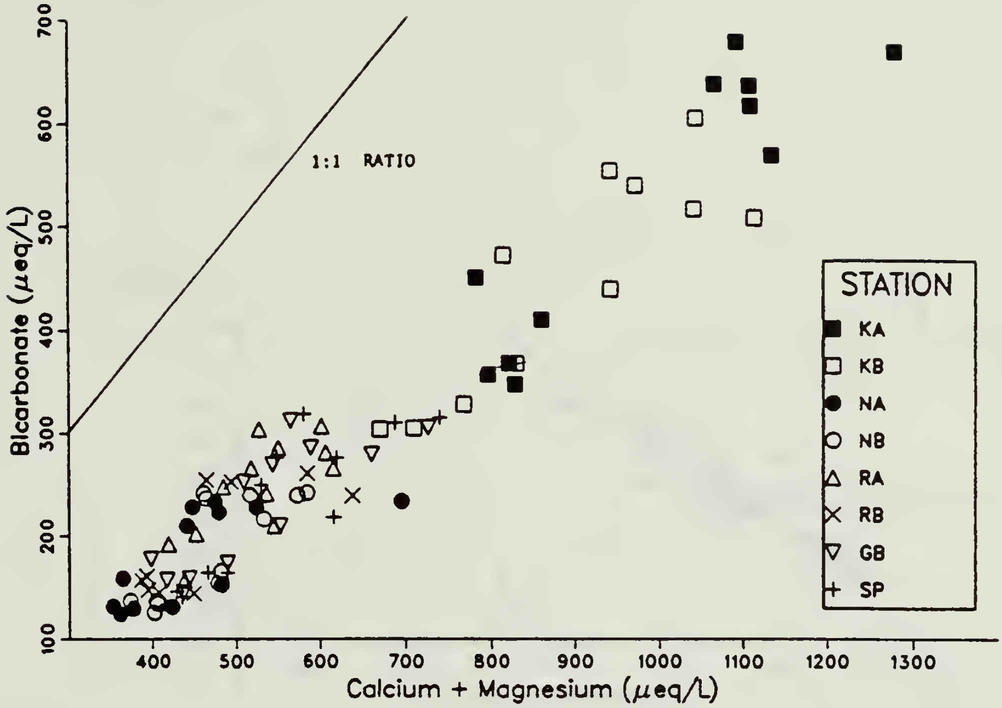


Figure 24. Relation between HCO_3^- and Ca^{+2} plus Mg^{+2} (μeq L^{-1}) as mean monthly values for main lake stations.

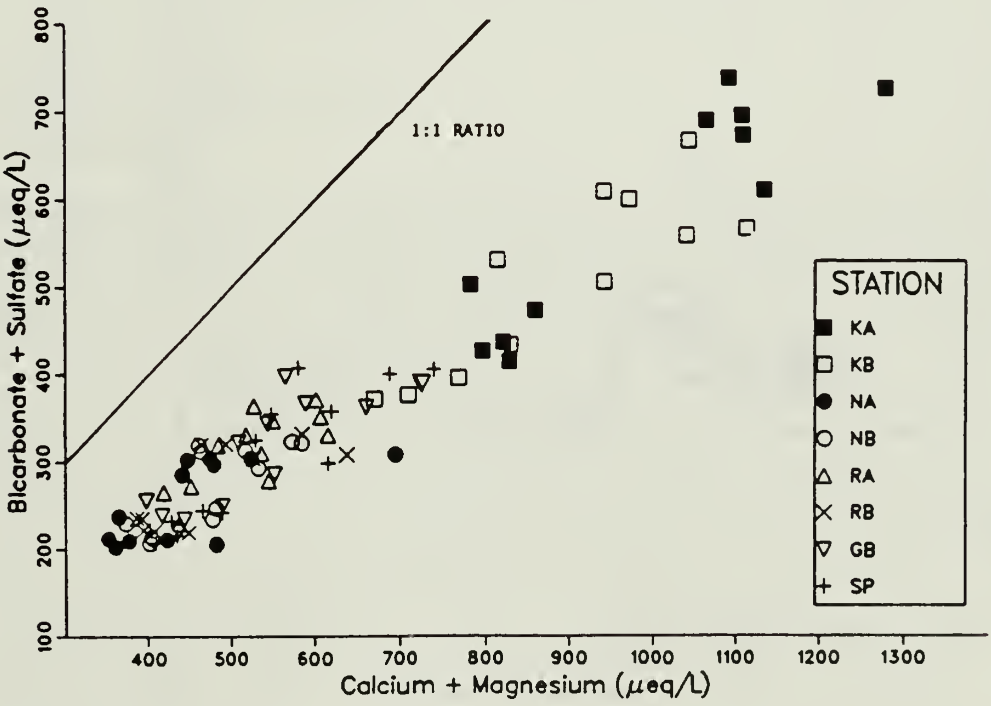


Figure 25. Relation between HCO_3^- plus SO_4^{-2} and Ca^{+2} plus Mg^{+2} (μeq L^{-1}) as mean monthly values main lake stations.

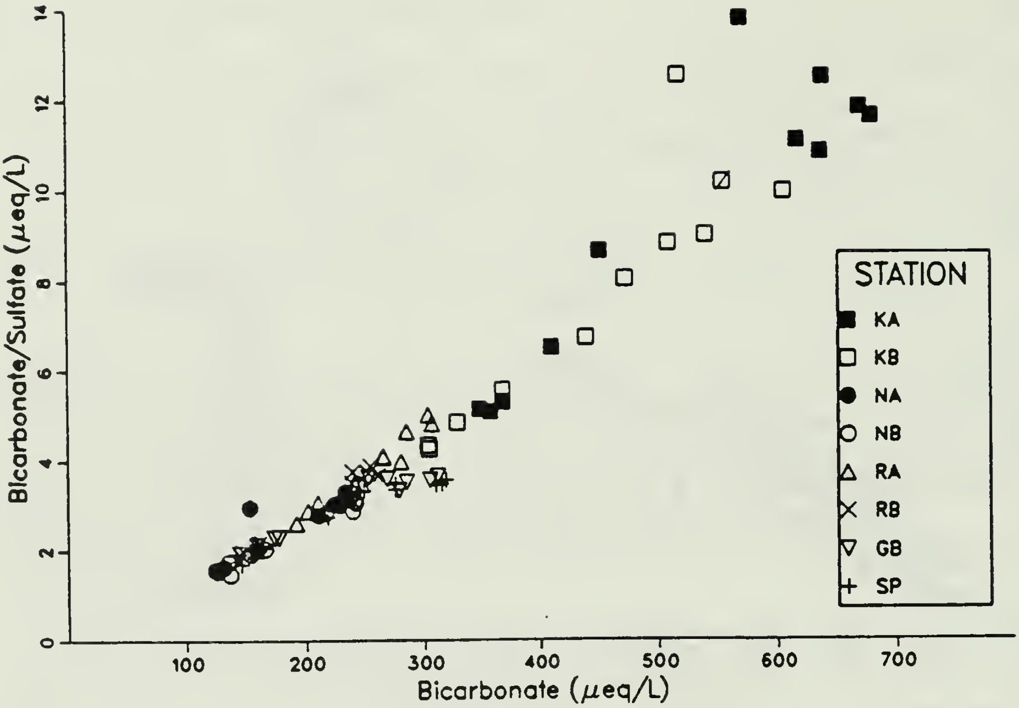


Figure 26. Relation between HCO_3^- over SO_4^{-2} and HCO_3^- (μeq L^{-1}) as mean monthly values for main lake stations.

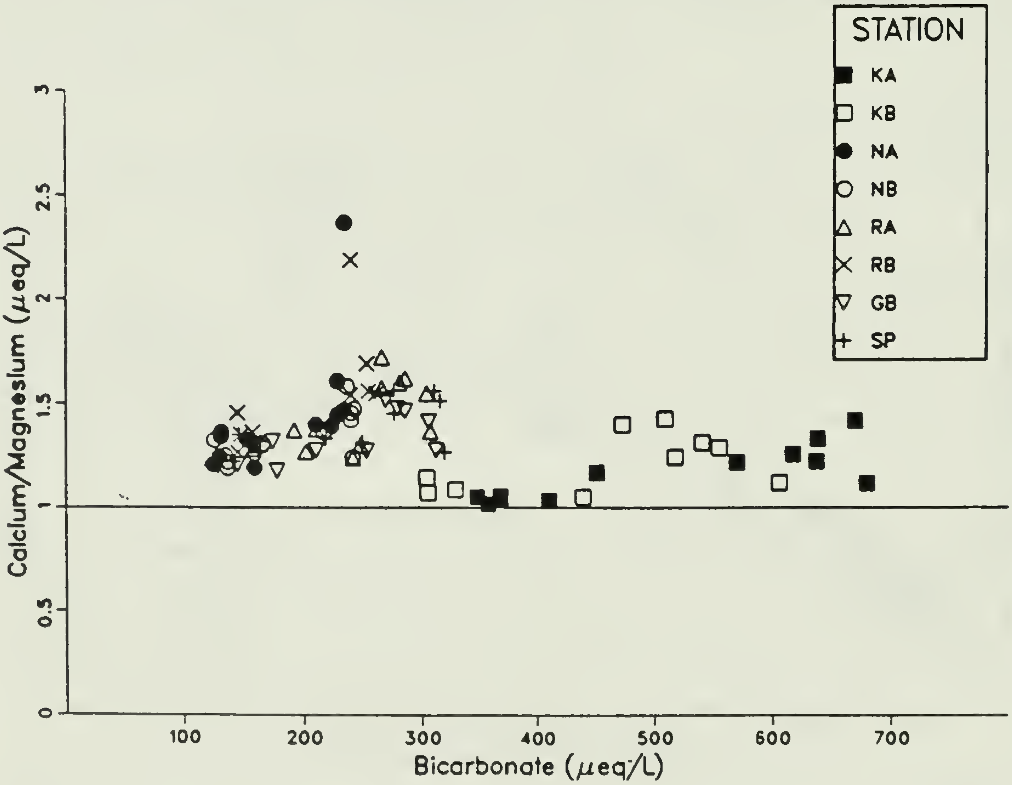


Figure 27. Relation between HCO_3^- and Ca^{+2} over Mg^{+2} (μeq L^{-1}) as mean monthly values for main lake stations.

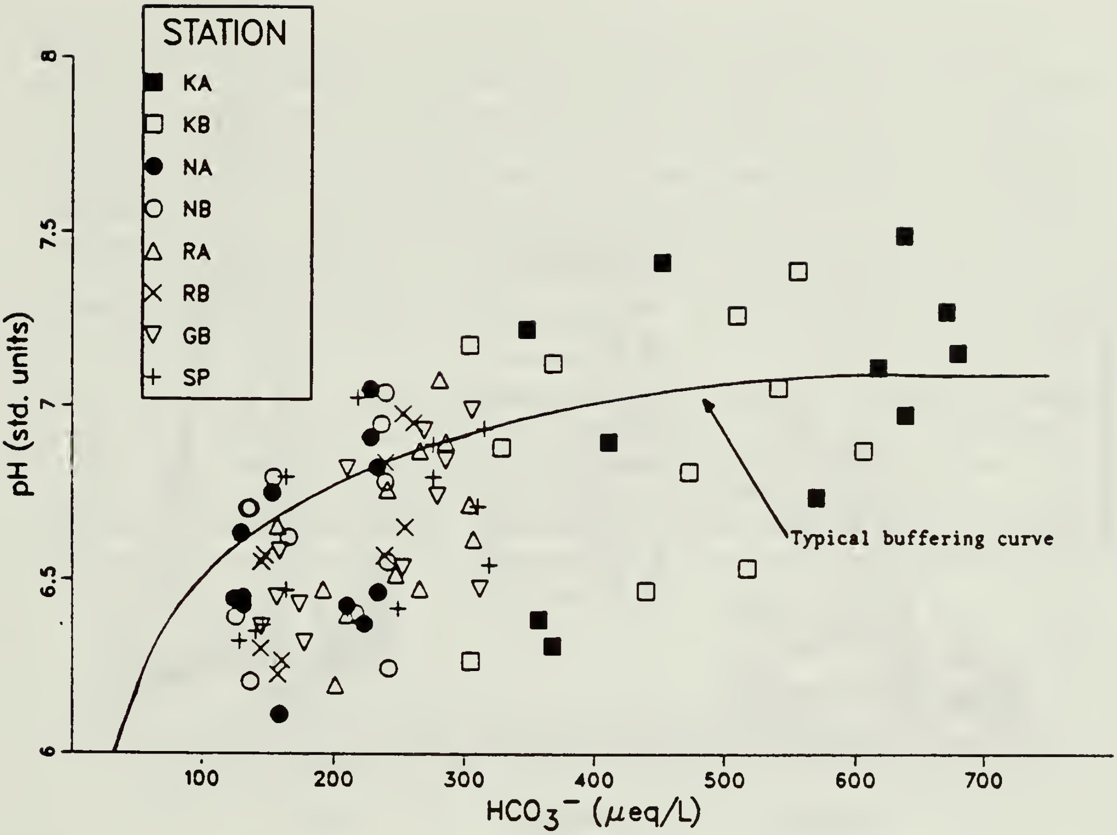


Figure 28. Relation between HCO_3^- (μeq L^{-1}) pH (std. units) as mean monthly values for main lake stations.

Biological Characterization

Chlorophyll-a:

Chlorophyll-a (chl-a) concentrations are an accurate, simple and inexpensive means of estimating phytoplankton standing crop (biomass). Seasonal changes in phytoplankton biomass are readily observed in plots of pigment concentration over time. Stations in both Rainy and Namakan lakes maintained consistently low chl-a concentrations throughout the two summer sampling seasons, with values never rising above 6 mg m-3 (Fig. 29). Values in this range (<6 mg m-3) are typical of those for northwestern Ontario's Canadian Shield lakes in the ELA (Schindler 1971, Schindler and Holmgren 1971, Schindler and Nighswander 1970, Fee 1976, Armstrong and Schindler 1971), for oligotrophic lakes off the Precambrian Shield in Alberta, Canada (Prepas and Trew 1983), for lakes in coastal British Columbia (Stockner and Shortreed 1984), arctic Alaskan lakes (Miller et al. 1986), New York lakes (Oglesby and Schaffner 1978), Mirror Lake, New Hampshire (Likens 1985), and even for several lakes in New Zealand (Pridmore et al. 1985).

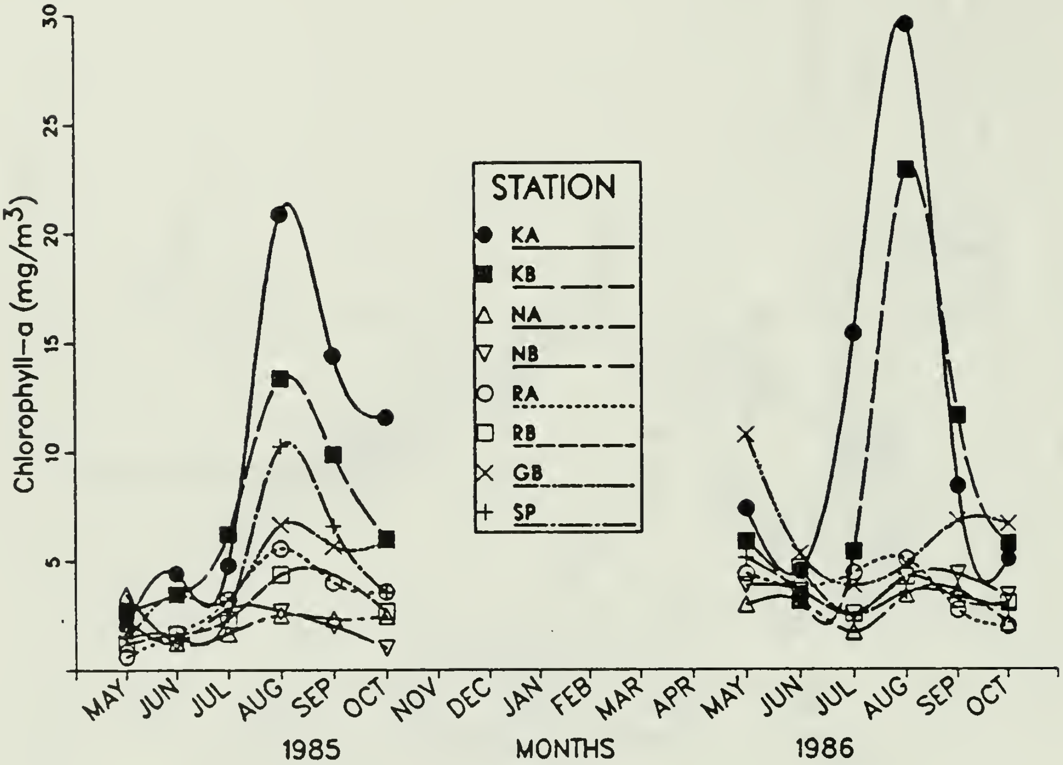


Figure 29. Mean chlorophyll-a concentrations (mg m^{-3}) for main lake stations (0.5, 1, 3, 5, and 10 m).

Peak chl-a concentrations occurred most often in August, and as expected, stations KA and KB maintained much higher concentrations over most of the summer. Chlorophyll-a concentrations increased by nearly five-fold at station KA between July and August, 1986, reaching the highest mean level observed that year (20.88 mg m^{-3}). The mean concentration in August of 1986 at KA was even higher (30.11 mg m^{-3}). Seasonal patterns in chl-a concentrations in Kabetogama Lake follow a similar pattern to those observed in Shagawa Lake (located less than 100 km southeast of Kabetogama). Mean concentrations there ranged from 15 to 25 mg m^{-3} during June and July, increased to a maximum of 150 mg m^{-3} during an August bloom of Aphanizomenon sp., and then decreased rapidly in early September (Megard and Smith 1974). Theoretical maximum values possible under optimum conditions are around 100 mg m^{-3} (Wetzel 1975). The high vertical extinction coefficients (largely the result of humic and tannic acids) result in a lowering of the maximum chl-a and productivity levels possible in clearer waters. For VOYA lakes, lowest mean levels measured occurred at station NB in October, 1985 (1.01 mg m^{-3}). In general, the station ranking of summer chl-a concentrations is: KA > KB > SP > GB > RA & RB > NA & NB.

Appendix E(1) includes "balloon" and three-dimensional surface plots of chl-a concentrations at specific depths (0.5 to 10-m), over the 1985 sampling season (month 5.0 = May, 6.0 = June, etc.). They are included to stress the fundamental difference in algal standing crops which were observed at the Kabetogama stations as compared to the other six primary sampling sites. The vertical scales (chl-a in mg m^{-3}) are identical for all of these plots. Included in Appendix E(2) are depth-time isopleths of chl-a concentrations (mg m^{-3}) for the primary sampling stations which span both years of study.

Mean chlorophyll-a concentration for the eight main stations was lower in 1985 (4.52 mg m^{-3}) than in 1986 (5.69 mg m^{-3}). Hargis (1981) also measured chl-a concentrations in Voyageurs lakes during June, July and August of 1979. Despite different extraction and measurement techniques, these data compare well to the mean concentrations obtained in the present study (Table 8).

Table 8. Summer mean chlorophyll-a concentrations (mg m^{-3}). Hargis data is from June, July and August of 1979.

Lake	Chlorophyll-a (mg m^{-3}) Hargis (1981)	Present study
Kabetogama	7.75	8.97
Namakan	2.11	2.74
Rainy	2.28	3.25
Sand Point	2.18	4.73

In a previous study of northern Ontario lakes (Kwiatkowski and Roff 1976), highly significant linear relationships were obtained between chl-a concentrations and pH's for the months of May thru August ($P < 0.01$). Combining mean monthly 1985 and 1986 data for the primary VOYA stations also yielded a significant linear relationship between these two variables ($P < 0.01$) for months from May to September, but not for October (Fig. 30). The regression line for the month of August was significantly different from the other months ($P < 0.01$). This is indicative of the high August levels of chl-a and implied peak in algal biomass at most stations during this month. In all months increasing mean chl-a concentrations were accompanied by increasing pH's and alkalinities. Lowest mean chl-a concentrations were observed for stations NA and RB, which were also the sites of lowest mean pH.

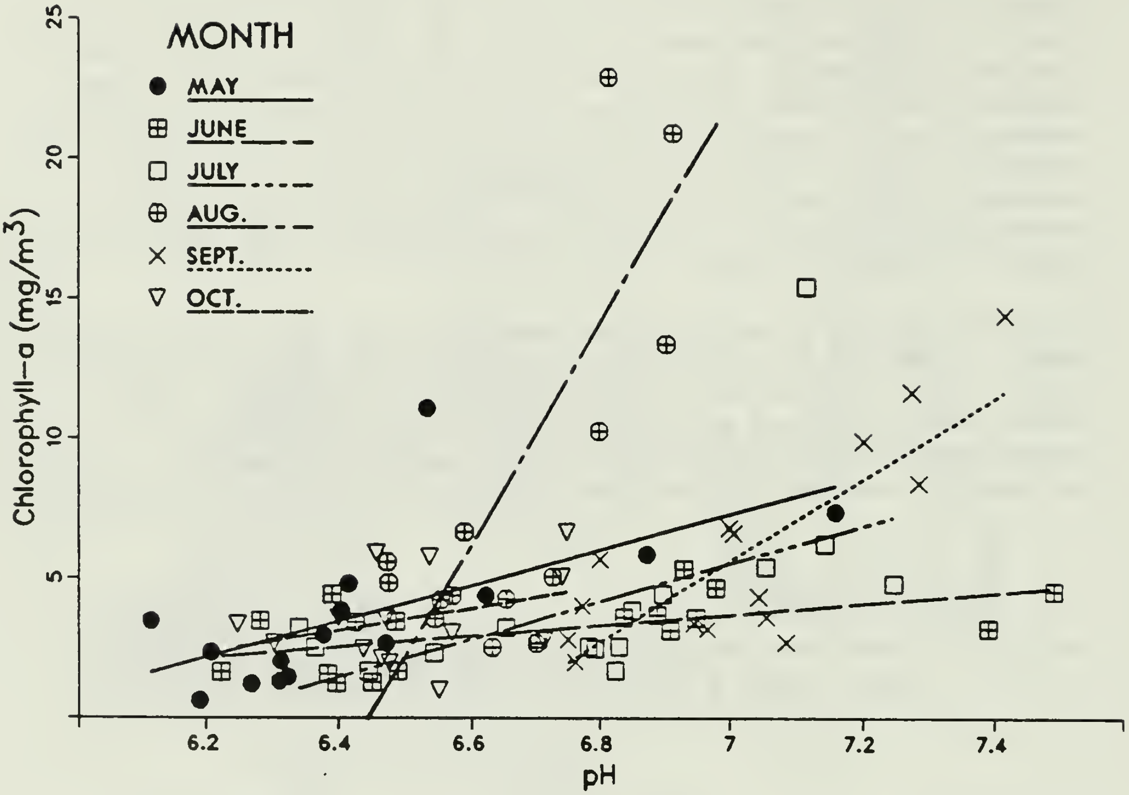


Figure 30. Relationship between mean pH and mean chlorophyll-a concentrations for main lake stations (0.5, 1, 2, 3, 5 and 10 m) grouped by month, Voyageurs National Park.

Trophic State Indices:

Based upon summer chl-a concentrations a trophic state index (Carlson 1977) has been applied to the VOYA lakes. This trophic state index (TSI) places natural waters upon a numerical gradient from 0 to 100, thus eliminating the arbitrary divisions between oligo-, meso-, and eutrophic states. Each major division of 10 (10, 20, 30, etc.) represents a doubling of algal biomass. Carlson suggests that for purposes of classification the chlorophyll-based index is the one best applied during summer months, however changes of less than 5 TSI units have been found to be indistinguishable from the inherent "noise" in available data (Spacie and Bell 1980). The computational form of the equation used is:

$$TSI(Chl) = 10 (6 - (2.04 - (0.68 \ln Chl)) / \ln 2)$$

Where: Chl = chlorophyll-a (mg m^{-3})

Previously, TSI values for VOYA lakes were calculated from surface, thermocline, and hypolimnion chlorophyll concentrations when lakes were stratified, with the mean of these three values over June, July and August used to represent an average TSI value for each lake station (Hargis 1981). Table 9 presents the mean TSI values obtained by Hargis during the summer of 1979 on a lake by lake basis as compared to those obtained during 1985 and 1986 in the present study. Current TSI's are based on mean chl-a concentrations from samples at 0.5, 1, 3, 5 and 10m at the two main stations in each lake. The Hargis data have been converted from multiple station to lakewide means (Kabetogama = 5, Namakan = 3, Rainy = 3 and Sand Point = 2 stations originally sampled).

Table 9. Mean monthly TSI values for each of the four main VOYA lakes as obtained in a previous (Hargis 1981) and the present two-season study.

	Trophic State Index		
Lake (Month)	Hargis 1979	1985	1986
Kabetogama			
June	46	44	45
July	52	49	55
Aug.	65	58	64
Namakan			
June	46	34	43
July	42	40	40
Aug.	44	41	46
Rainy			
June	50	36	45
July	41	41	45
Aug.	53	43	46
Sand Point			
June	50	43	47
July	40	42	44
Aug.	46	54	45

Mean monthly TSI values on a lakewide basis ranged from 34 (Namakan- June, 1985) to 64 (Kabetogama- August, 1986). TSI's are comparable to those calculated by Hargis for 1979 data. Combining TSI values from both studies shows highest TSI's are obtained in August for each of the four lakes. No definite trends in TSI's between 1979 and 1986 are obvious. However, values obtained in 1986 of the present study are closer to those of 1979. These TSI values should serve as standard measures for the average trophic conditions of the VOYA lakes, useful in detecting long-term change and making informed lake management decisions.

Total Organic Carbon:

The expected range of total organic carbon (TOC) in natural waters is roughly 1 to 30 mg L^{-1} (ppm); higher values are usually encountered only under polluted conditions. The average values from over 500 Wisconsin lakes for the two components of TOC were dissolved organic carbon (DOC), 15.2 mg L^{-1}, and particulate organic carbon (POC), 1.4 mg L^{-1} (Wetzel 1975). Total organic carbon values obtained in the present study ranged from 3.1 to 27.1 mg L^{-1} (May 4 and June 28, 1986, respectively, at station KB). As with TKN, TOC data was collected most frequently at station KB during 1986. For all stations sampled, mean TOC = 11.07 mg L^{-1} (SD = 3.92, n = 68).

Concentrations of TOC at station KB were somewhat erratic through the summer of 1986 (Fig. 31). Concentrations rose between early and late May, coincident with peak runoff effects and reservoir refilling. Total organic carbon values at the Kabetogama stations were within the limits of concentrations observed at other sites (roughly 8 - 18 mg L^{-1}), except in early May and on one sampling date in late June. The unusually high TOC value reported for June 28, 1986 at station KB appears to be anomalous. However, since replicate samples were not analyzed there are no firm grounds to support the rejection of this point from the data set.

No general pattern in TOC is evident and it is unlikely that carbon plays any limiting role in primary production or phytoplanktonic standing crop. Concentrations of TOC show no correlation to total biomass (chl-a), nor to C-assimilation rates. Relatively high concentrations of DOC in the form of various organic acids are likely responsible for the lack of relationship between production estimates and TOC concentrations.

Total organic carbon was weakly correlated with TKN ($P < 0.2$, n = 60). The ratios of TOC:TKN ranged from 7.4 to 75.3 (mean = 24.9, SD = 10.1, n = 60). Ratios observed at station KB closely follow the pattern of TOC concentrations in general (Fig. 32). Again, the anomalously high TOC:TKN ratio obtained for June 28, is due to the extreme TOC concentration reported for that sample while TKN concentration remained at a typical level. Possible explanations for this are numerous but uncertain.

The initially TOC-rich organic matter of terrestrial and marsh sources undergoes decomposition enroute to open lake waters. In general, allochthonous organic matter will have a C:N ratio of roughly 45:1 (Hutchinson 1957), with a DOC component rich in humic acid compounds that are low in N content, and give the water a stained brown color. Autochthonous organic matter, produced within the lake by the decomposition of phytoplankton, will have a much lower C:N ratio of about 12:1 (Wetzel 1975). This explains the general downward trend in TOC:TKN ratios which began in early July 1986, and coincided with the increase in proportion of autochthonously derived organic matter, biomass, and primary production at station KB.

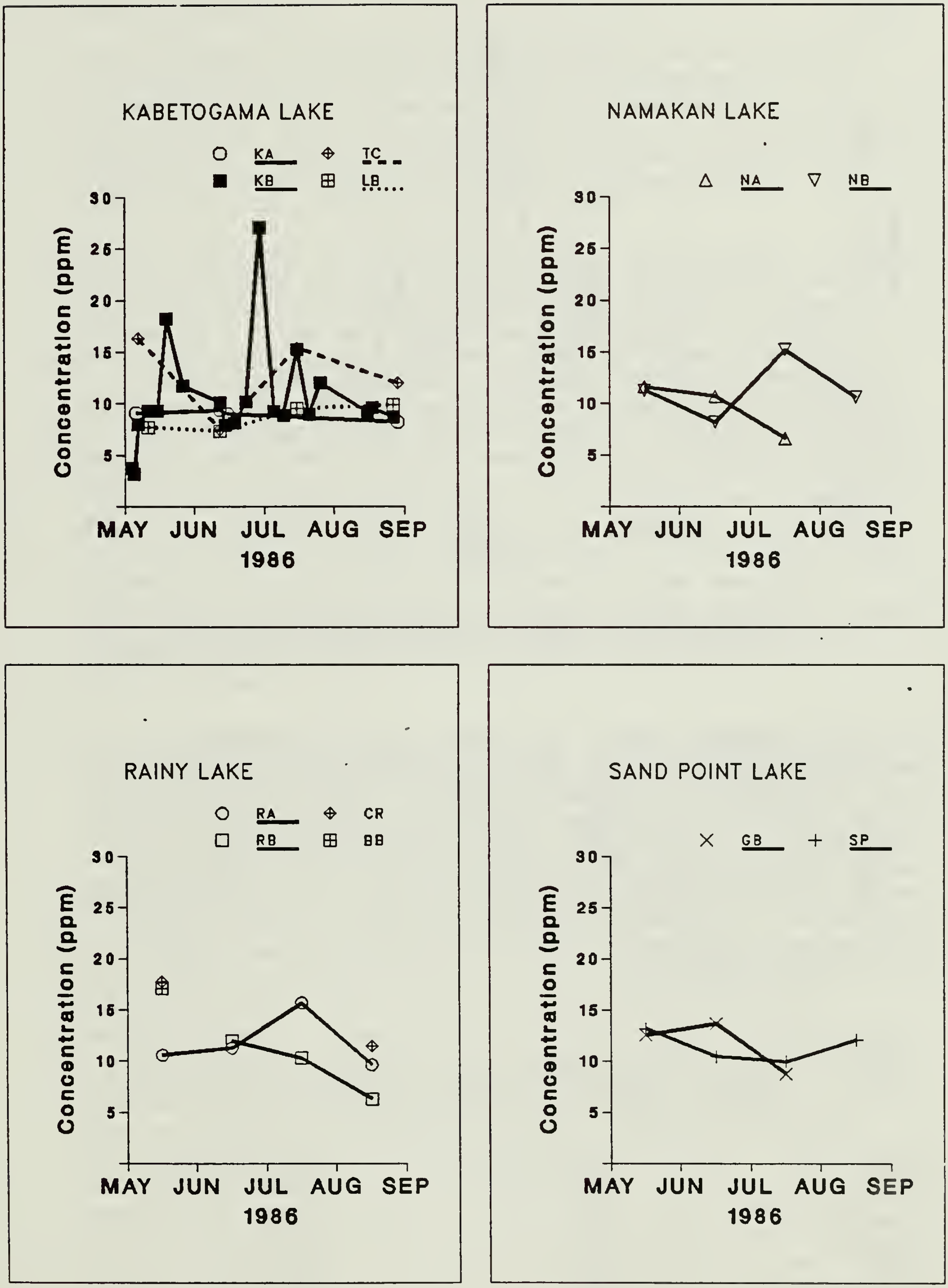


Figure 31. Total organic carbon (mg L^{-1}) at 1 m for the main lake stations and four grab-sample sites during 1986.

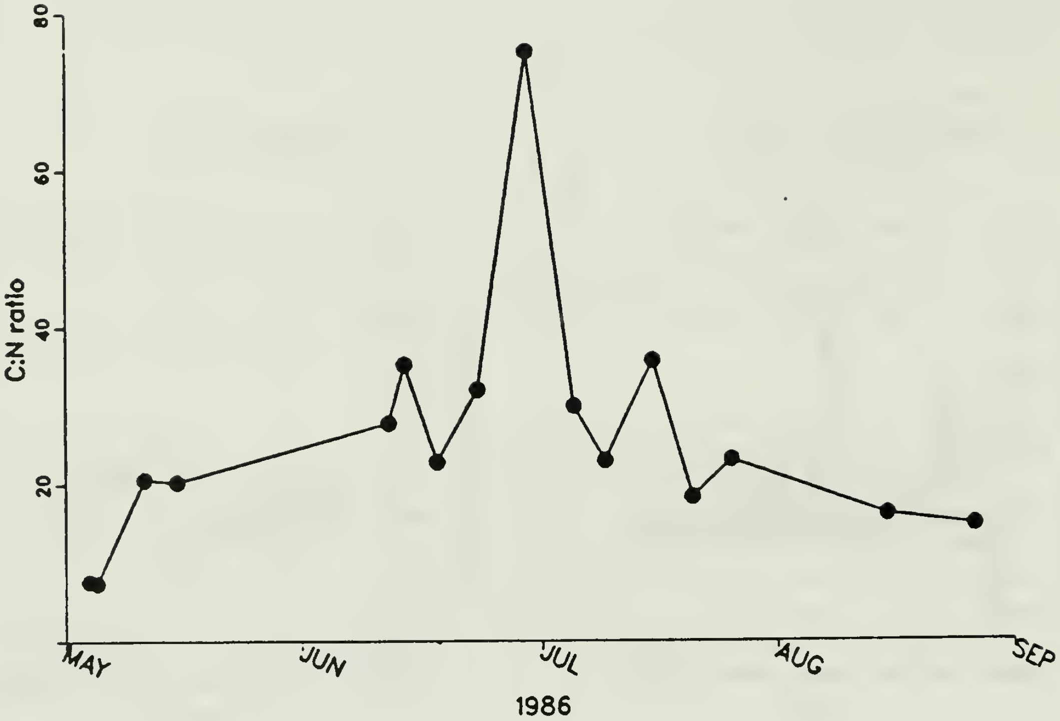


Figure 32. Total organic carbon to total kjeldahl nitrogen ratios for station KB during 1986, Voyageurs National Park.

Mean TOC concentrations for Kabetogama Lake did not differ markedly from those of the other three lakes, yet the mean TOC:TKN ratio was lower in Kabetogama (Table 10). This may be indicative of the greater relative importance of autochthonous sources of organic matter in Kabetogama. At productive shallow-water grab-sample sites, the mean TOC:TKN ratio was similar to Kabetogama's, though TOC concentrations were higher. The highest mean ratio was observed in less-productive Rainy Lake which is least influenced by lake level drawdowns on the basis of percent volume reduction and exposed bottom area.

Table 10. Mean TOC concentrations and TOC:TKN ratios for May - October 1986 for main VOYA lakes and grab-sample sites.

Lake	TOC (mg L^{-1})	TOC:TKN ratio
Kabetogama	10.5	20.8
Namakan	10.5	27.5
Rainy	10.5	29.8
Sand Point	10.9	26.8
Grab-sample sites	12.1	20.6

Carbon Assimilation:

The ^{14}C method of measuring production permits an estimation of the in situ rates of photosynthesis approximating net productivity; however, these estimates are comparable only in a general manner. There are several advantages in the ability to measure assimilation rates directly in the field, yet the proper perspective dictates that these values be viewed only as approximations of net primary productivity.

Confining plankton in bottles disrupts natural pathways of nutrient regeneration (Gieskes et al. 1979, Eppley 1982), while preventing vertical movement through strata of varying light intensities. Recent work has attempted to assess the harmful effects of sampling and containment involved in the conventional ^{14}C method of measuring primary production (Cullen et al. 1986). Damage to phytoplankton during membrane filtration is also common, but the exact magnitude of error that this introduces into primary production measurements has not been determined (Arthur and Rigler 1967).

Vertical profiles of C-assimilation rates indicate that in almost all cases the large majority of productivity was occurring in the top meter of the water column. This was the case whether incubations were at 0.5, 1, 2 and 3 m, or at 0.5, 1, 3 and 5 m (Fig. 33). Variance and ranges in C-assimiltion rates are also greater at depths closer to the surface when data from all stations is pooled.

The monthly succession of productivity is fairly irregular, and fluctuations are often marked. This is in contrast to the more consistent (less "choppy") seasonal patterns of productivity common in more oligotrophic systems. It has been shown that the effects of algal utilization and resulting reduction in critical nutrients to levels that limit certain algal groups can progress rapidly (Wetzel 1975). This may be a major causal factor in the observed oscillations in these composite C-assimilation rates.

A wide range of values and monthly patterns in productivities (ie., C-assimilation rates) were observed at the eight main sampling stations. Nearly all stations exhibited distinctly bimodal patterns in productivity during 1985 (Fig. 34), with peaks occurring in June and August (May and August at SP). Stations KA and KB were more productive than other stations throughout, except in May when they were the sites of lowest productivity. During 1985, all stations, except SP showed increased productivities between May and June, followed by decreases into July. Reduced C-assimilation rates in July 1985 may be due to dilution effects stemming from unusually high runoff volumes at that time (Fig. 5), yet reductions in mean chlorophyll-a concentrations were not observed. Nitrogen limitation effects may also have played a role in reduced July productivities, as the lowest TKN concentrations and highest TOC:TKN ratios occurred between mid-June and early-July (Figs. 21 and 31).

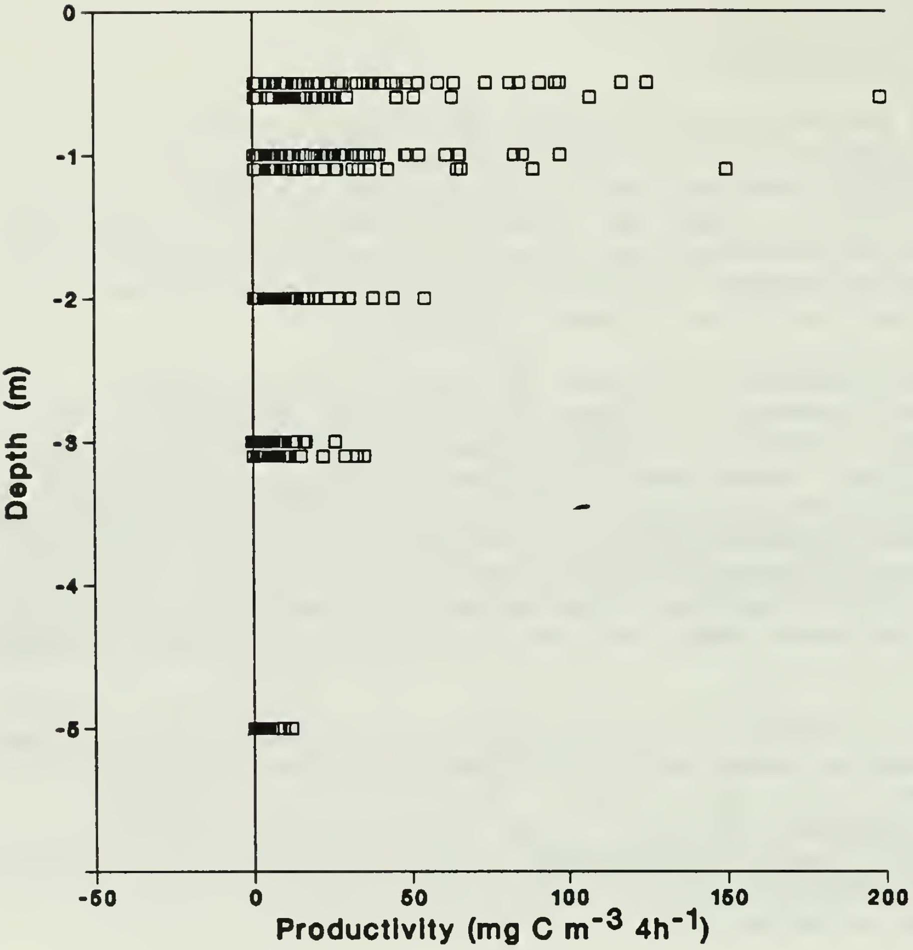


Figure 33. Distribution by depth (m) of all C-assimilation rates (mgC m^{-3} 4hrs^{-1}) for the main lake stations.

Between July and August production values sharply increased (KA, KB, SP, RB), remained fairly constant (NA, NB, RA), and in one case (GB) decreased. Greatly reduced values at the more productive stations were then observed in September and October, as the Kabetogama stations maintained their higher productivities even into these last two months.

Depth-time distributions of phytoplanktonic production rates illustrate the seasonal and interstation variations that were encountered in the VOYA lakes (Appendix F). Contour intervals in Appendix F figures are 5.0 mgC m^{-3} 4hrs^{-1}. The general pattern is for increasing production thru the spring following ice-out, with greatest C-assimilation occurring in the surface trophogenic zone down to one or two meters. Productivity peaks appear to occur earlier in Namakan and Rainy Lakes (May or June) than in Kabetogama (August), though this may vary from year to year.

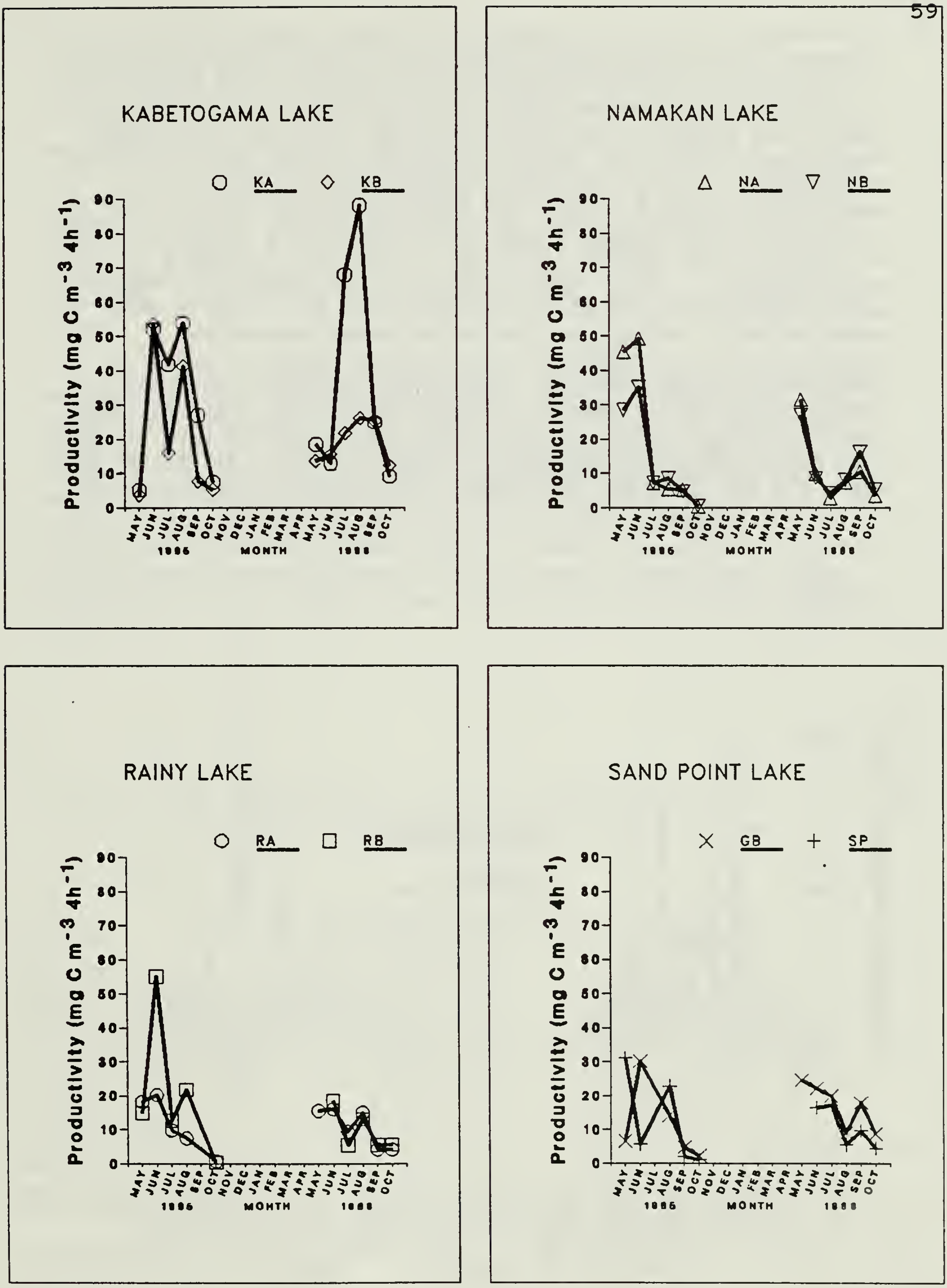


Figure 34. Mean carbon assimilation rates (mgC m^{-3} 4h^{-1}) for main lake stations, upper 5 m, over the two sampling seasons, Voyageurs National Park, MN.

The between-station relationships in August productivities coincide quite well with observed chl-a concentrations, ie. KA > KB > SP > other sites, although station GB was not as productive in August as might be expected based upon chl-a concentrations alone. The highest observed productivity occurred at the same station and time as the peak chl-a concentration (KA in August of both years). As with mean chl-a concentrations, mean C-assimilation rates for the eight main stations as a whole (0.5, 1, 2, 3, and 5m) was higher during the 1985 sampling season (17.9 mgC m^{-3} $4hrs^{-1}$) than in 1986 (16.2 mgC m^{-3} $4hrs^{-1}$). A highly significant ($P < .001$), almost identical, correlation between C-assimilation rates and chl-a concentrations was found in both years as well. Strong positive correlations between chl-a concentrations are commonly found in north-temperate lakes. Combining 1985 and 1986 data, Kabetogama Lake had significantly higher ($P < 0.05$) volumetric C-assimilation rates than the other lake stations (Fig. 35). Productivity data for Rainy Lake stations were not obtained for the month of September 1985, for RB in May 1986, and for SP in May 1986, due to poor weather conditions.

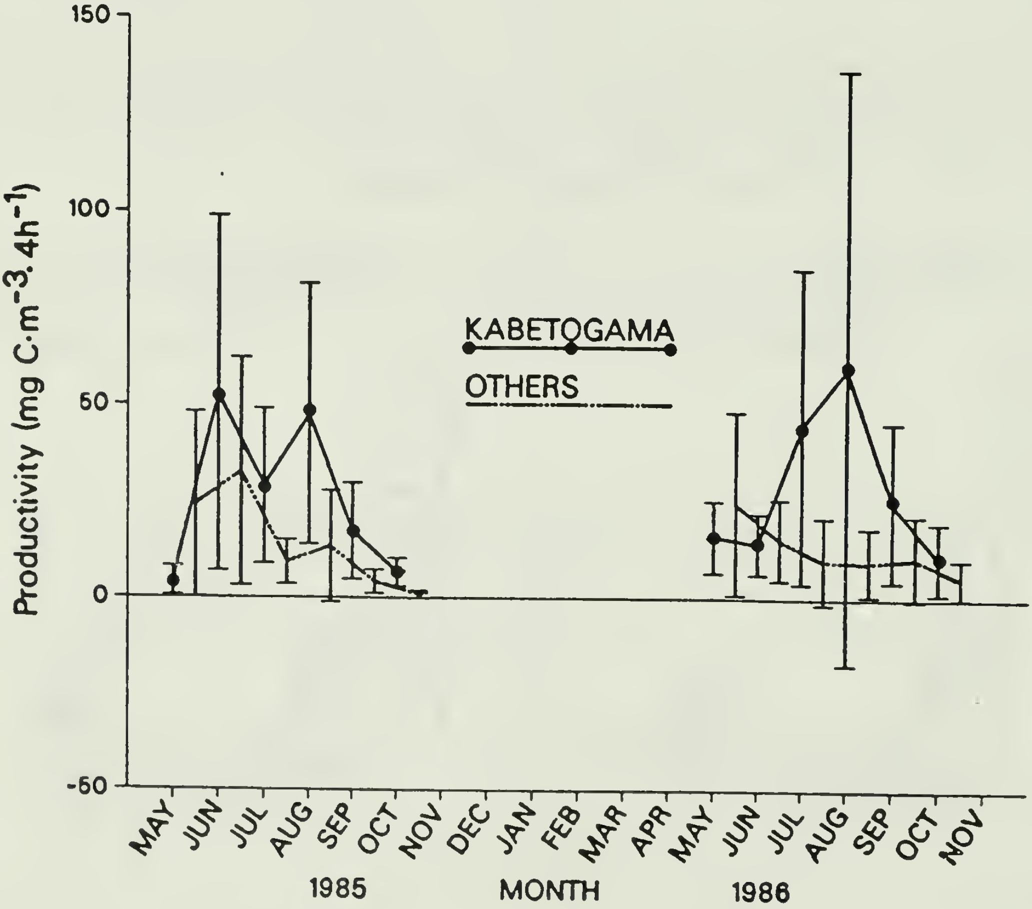


Figure 35. Means and standard deviations of volumetric production rates (mgC m^{-3} $4h^{-1}$), in the upper 5 m, comparing Kabetogama to the other pooled study lakes.

Volumetric production in several northwestern Ontario lakes extended from 0.02 to 2.12 gC m^{-3} day^{-1} (Schindler and Holmgren 1971). If the gross assumption that 50% of daily production is accounted for in the 4-hr incubation periods is accepted, then the present range for VOYA stations is roughly 0 to 396 mgC m^{-3} day^{-1}. For all dates, stations, and depths sampled in both 1985 and 1986, the mean volumetric C-assimilation rate was 17.1 mgC m^{-3} $4hrs^{-1}$ (range = -0.53 to 198.13, SD = 23.9, n = 368) Productivity for a hardwater lake of low productivity (Lawrence Lake, Michigan) ranged from approximately 0.0 to 80.0 mgC m^{-3} day^{-1}, although these are specific, not mean values for more than one depth (Wetzel 1975).

For comparative purposes, productivity data are often presented on an areal rather than volumetric basis. When data from discrete depths are integrated over a square meter of water column, rates of in situ production per unit surface area result. Whether volumetric or areal expressions of productivity rates are more suitable for trophic studies has been discussed by Sager, et al. (1984); who examined the behavior of areal and volumetric production rates over a wide range of trophic conditions. Areal production estimates obtained in this study are comparable with, but generally lower than, values reported for other inland waters (Table 11).

Table 11. Net areal primary production (mgC m^{-2} day^{-1}) estimates obtained in this and previous studies

Site/s	Primary Production (mgC.m-2.day-1) Range (mean)	Source
VOYA lakes (4)	3-412 (93)*	Present study
Lake Michigan	250-648 (422)	Fahnenstiel & Scavia 1987
Lake 226 of the ELA	223-537 (401)	Bower, et al. 1987
Portuguese reservoirs (3)	159-409 (---)	Cabecadas & Brogueira 1987
Toolik Lake, Alaska	16-228 (103)	Miller, et al. 1986
Sri Lankan waters (10)	680-2470 (495)	Silva & Davies 1986
W. Ontario lakes (6)	4-130 (37)**	Kwiatkowski & Roff 1976
Lawrence Lake, Michigan	84-127 (113)	Wetzel 1975
ELA lakes (20)	179-1103 (---)	Schindler & Holmgren 1971
Clear Lake, E. Ontario	100-2570 (1020)	Schindler & Nighswander 1970
Sudbury, Ontario lakes (3)	[illegible]-126 (77)	Johnson, et al. 1969
Douglas Lake, Michigan	64-218 (158)	Saunders, et al. 1965
Grand Traverse Bay	295-536 (456)	Saunders, et al. 1965

* Assuming 50% of daily production occurred during the 4-hr incubation period.
** mgC.m-2.hr-1

The mean maximum summer production for most ELA lakes was about 400 mgC m^{-2} day^{-1}. Only extremely oligotrophic lakes and very shallow lakes exhibited lower areal production values (Schindler and Holmgren 1971). Values reported here for the VOYA lakes certainly underestimate actual areal production. First, production has been integrated only to a depth of 5 m, therefore failing to reflect production occurring below this depth. Secondly, errors in filtration (Arthur and Rigler 1967) were not corrected for in this study. Filtration error in ELA studies ranged from 1.2 to 6.1 times uncorrected filter activities (Schindler and Holmgren 1971). Finally, release of extracellular organic products by the enclosed phytoplankton was never quantified. Although production of extracellular products during 4-hr incubations in Canadian Shield waters was generally negligible (less than 1% of total light bottle fixation) (Schindler and Holmgren 1971), high production of extracellular products has been found in other phytoplankton assemblages (Nalewajko 1966). A combination of these factors has likely led to underestimations of net primary production values in this study.

Between-lake comparisons of seasonal variation in areal net production rates points out the relatively high productivity in Kabetogama Lake (Figure 36).

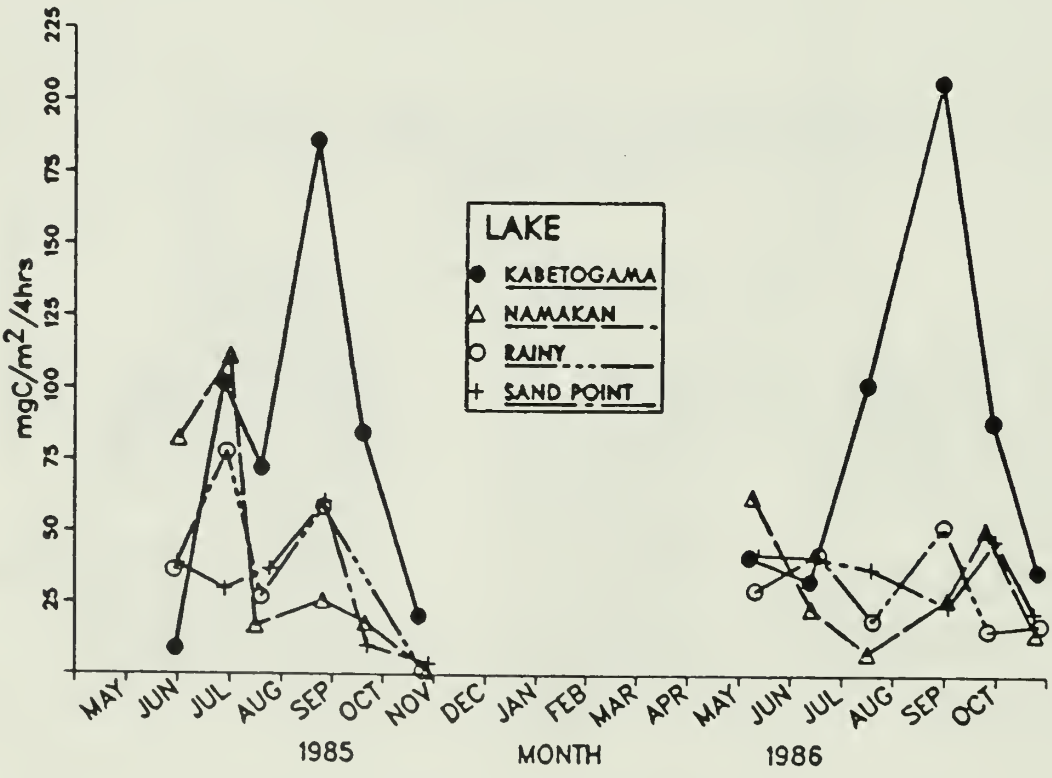


Figure 36. Integrated areal productivity (mgC m^{-2} $4h^{-1}$), for the main VOYA lakes, upper 5 m, over the two sampling seasons, Voyageurs National Park , MN.

As mentioned previously, it is not unexpected that seasonal fluctuations within productive lakes are more irregular and marked than in unproductive ones. Despite internal variations in the seasonal rates of productivity, the different dates that incubations were performed, and the many sources of error; areal production values remained fairly constant between 1985 and 1986. Ideally, annual primary production values reported on a whole-lake basis would serve as better indicators of long-term changes in the trophic states of the VOYA lakes than the monthly areal values presented here.

On a volumetric basis, maximum production occurred between a pH of 6.8 and 7.2. Minimum values occurred between a pH of 6.3 and 6.5. Figure 37 displays production per unit volume plotted against pH. The dashed line represents the significant non-linear relationship ($P < 0.01$) fitted to such data in a previous study (Kwiatkowski and Roff 1976), where production ranged from 0.6 to 47.7 mgC m^{-3} hr^{-1}. The high seasonal variability in production and narrow range of pH values encountered in the VOYA lakes have yielded data which do not follow the relationship obtained previously. Nevertheless, a significant correlation ($P < 0.01$, $R^2 = .144$, $n = 368$) between pH and volumetric production did exist.

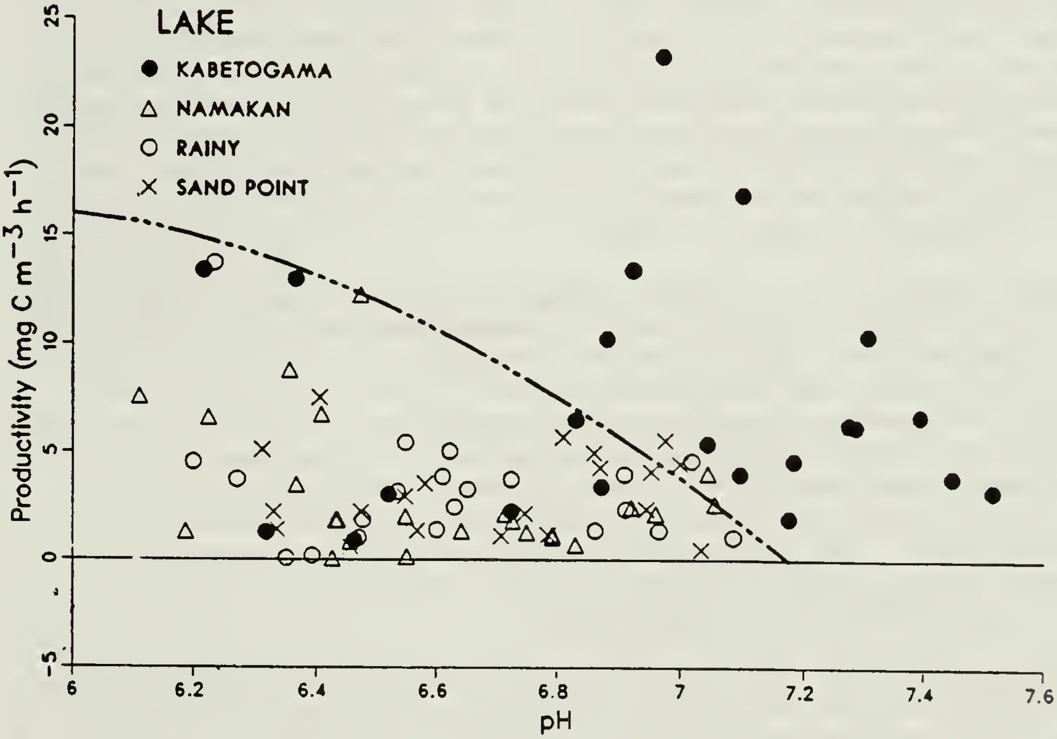


Figure 37. The relationship between mean pH and mean volumetric productivity (mgC m^{-3} h^{-1}) for the main VOYA lakes (0.5, 1, 3 and 5 m), Voyageurs National Park, MN.

Species Composition:

Qualitative analysis of preserved plankton samples has been performed only for samples collected during August (all stations) and for stations KA and KB during October. At this time no quantitative data exist on species composition and diversity. A listing by station of the major genera thus far observed is presented in Table 12.

Kabetogama Lake seems to experience a minor bloom of diatoms directly following ice-out. This is followed by a massive growth of blue-green algae during the summer months (mid-June thru September), which corresponds to peak areal production and chl-a concentration values. The summer flora is dominated by Aphanizomenon flos-aquae which typically blooms in waters receiving agricultural runoff (Barica 1975, Jones and Bachman 1975, Shaw et al., 1981) and high phosphorus loading (Sager 1971, Vanderhoef et al. 1974). As chl-a concentrations decrease, the autumnal phytoplankton community becomes dominated more by the large centric diatoms Melosira sp. and Stephanodiscus sp.

Although phytoplankton were not sampled in August, the species compositions reported in the RBI of 1973 appear quite similar to those seen in 1985 (NPS 1973). The blue-green Aphanizomenon flos-aquae is most probably the dominant community member during most of the summer, particularly in Kabetogama and Sand Point Lakes. An examination of the relationship between mean chl-a concentration and percent composition of phytoplankton standing crop has previously indicated that the more productive VOYA lakes (specifically Kabetogama) are dominated by blue-greens (Hargis 1981). The increase in numbers of these larger blue-green algae is likely to follow the same pattern as that observed for changes in chlorophyll-a concentrations.

Summer blooms of the N-fixing Aphanizomenon flos-aquae result in large inputs of N, particularly in Kabetogama Lake (Fig. 21). This species has a high N content, roughly 9% of total dry weight (Prescott 1960), and a high average N:P ratio of 83.4 (Sullivan 1978). A previous study found that populations of blue-greens and flagellates were reduced in the upper end of a southern Ontario reservoir when water levels were lowered. Phytoplankton population densities below the dam increased at the same time (Duthie 1968). At this point, spatial and seasonal patterns in phytoplankton population numbers in the VOYA lakes can only be inferred from chl-a concentrations.

Kabetogama Lake is not only distinct in terms of morphology, water chemistry and productivity. Kabetogama Lake supposedly had more than twice the overall summertime average zooplankton density of Sand Point and Rainy, and three times that of Namakan Lake (Hargis 1981). Average densities of benthic invertebrates were found to be lower and roughly equal in Rainy, Namakan and Sand Point Lakes, but 2.7 times greater in Kabetogama Lake.

Table 12. List of observed phytoplankton genera for August 1985 at all main lake stations, and for October 1985 at stations KA and KB (* = most abundant).

	KA	KB	NA	NB	RA	RB	GB	SP	KA^{O}	KB^{O}
Aphanizomenon flos-aquae	X*	X*		X			X*	X*		
Anabaena sp.	X			X	X		X	X		
Stephanodiscus sp.	X		X	X					X	X
Asterionella formosa	X	X							X	X
Melosira sp.	X			X	X*	X*			X*	X*
Coelosphaerium sp.	X		X	X				X		
Tabellaria sp.	X			X	X				X	X
Synura sp.	X			X						
Mallomonas sp.				X						
Peroniella sp.	X	X								
Synedra sp.									X	X
Chroococcus sp.	X	X					X	X		
Microcystis sp.	X	X						X		
Derepyxis sp.	X									
Oscillatoria sp.	X								X	
Peroniella sp.	X	X								
Fragillaria sp.			X						X	X
Stipitococcus sp.		X								
Ceratium sp.						X				
Pediastrum sp.									X	
Pinnularia sp.									X	X
Cymbella sp.									X	
Cyclotella sp.									X	
Chrysochromulina sp.									X	
Gomphosphaeria sp.									X	
Oocystis sp.									X	
Gloeocystis sp.									X	

Also, diversity of invertebrates was lowered in the Namakan Reservoir lakes, particularly in the drawdown zone (Kraft 1986). In keeping with the higher production values observed in this study, Kabetogama Lake had the highest fish catch per unit effort by seining of all VOYA lakes for the 1984 season (Kallemeyn 1984). It is obvious that mean summer phytoplankton densities were greater in Kabetogama than in Namakan Reservoir lakes during 1985 and 1986, even without systematic enumeration. Preserved plankton samples for each month of the 1985 field season at each of the primary sampling stations await further analysis at MTU.

SUMMARY

Data obtained during both years of this study compare well with that obtained in previous studies of the same lakes (Table 13 for example), and with values obtained on a regional scale for other north-temperate lakes such as those in the ELA. Throughout this report, brief references to the literature have been used to make comparisons between the waters of VOYA and other similarly studied waters (see Results and Discussion).

Table 13. Comparison of ion concentrations for surface water (1 m) samples collected in October in east-Rainy Lake during the present study (1985 and 1986) and by USEPA (1986).

	1984 (EPA) Oct. 21	1985 Oct. 24	1986 Oct. 26
Temp. (°C)	11.1	10.1	9.3
pH (std. units)	7.18	6.33	6.60
Cond. (μmhos/cm)	41.4	38.0	43.0
Ca^{+2} (μeq L^{-1})	267.5	265.0	326.6
Mg^{+2} "	140.7	182.6	210.2
Na^{+} "	54.4	50.0	53.7
K^{+} "	15.6	15.1	13.6
NH_4^{+} "	1.0	0.0	1.3
NO_3^{-} "	2.4	4.8	4.1
SO_4^{-2} "	77.9	74.6	68.1
Cl "	17.8	15.9	20.9
HCO_3^{-} "	248.0	231.2	247.6
Sumcats. "	478.2	512.7	605.4

On the basis of trophic state condition estimators (eg., specific conductances, chlorophyll-a concentrations and C-assimilation rates), it has been determined that statistically significant differences exist between Kabetogama Lake and the other lakes of the VOYA system. Apparently, Rainy, Namakan and Sand Point Lakes cannot be statistically singled out in terms of such parameters (Table 14). The non-drawndown Rainy Lake does not constitute a good control system with which to compare the Namakan Reservoir lakes, as it is fundamentally different in other hydrological and morphological respects.

Table 14. Ranked mean values for pH (standard units), alkalinity (mg L^{-1} $CaCO_3$), specific conductance (μmhos cm^{-1} @ 25° C.), chlorophyll-a concentration (mg m^{-3}) and volumetric carbon assimilation rate (mgC m^{-3} $4h^{-1}$) for the four study lakes over the entire study. Ordered means differ at $\alpha = 0.05$ by Newman-Keuls multiple range test.

pH	6.60	6.61	6.63	6.94
	Namakan	Rainy	Sand Point	Kabetogama
ALK.	11.3	13.6	13.7	29.3
	Namakan	Rainy	Sand Point	Kabetogama
COND.	45.1	47.1	50.3	83.5
	Namakan	Rainy	Sand Point	Kabetogama
CHL-A	2.69	3.27	4.00	9.27
	Namakan	Rainy	Sand Point	Kabetogama
^{14}C	12.9	13.2	13.8	29.4
	Rainy	Namakan	Sand Point	Kabetogama

The impact of changes in water levels on lake productivity and the phytoplankton community occurs through many mechanisms (Guseva 1958, Mitchell 1975, Serruya and Pollingher 1977, Vennie and Shaw 1979, Tundisi 1983). Fluctuations in water levels and the concurrent effects on nutrient availability (eg., total phosphorus) are major factors controlling seasonal patterns and variations in algal standing crops (Hodgkiss and Tai 1976). This is especially important if the lake's morphlogy is such that (1) a significant percentage of the lake's volume is removed with drawdown and (2) a significant portion of the littoral zone is exposed with drawdown. Both of these factors apply to Kabetogama Lake, where roughly 34% volume reduction, and 25% bottom area exposure accompany the 3 m drawdown.

It is concluded here that volume changes can influence limiting nutrient availability purely through concentration and dilution effects, even if inputs remain the same (see Model Results). In addition, maintenance of lakes at sub-natural levels can kill off the aquatic vegetation which flourishes in the drawdown zone, thereby increasing decomposition and nutrient remineralization with restored lake levels in the spring. As a result, more nutrients are released into the lake, increasing numbers and perhaps changing the species composition of primary producers.

The effect of minimizing the degree of drawdown imposed on Namakan Reservoir lakes will therefore reduce nutrient concentration effects and quite likely reduce nutrient loadings to the system from littoral sediments and vegetation.

Inclusion of environmental quality as an objective of water-resources development has made the planning process less susceptible to objective criteria and more dependent on the perceptions and subjective analyses of the planner (Biswas 1976). In other words, the objective of improving environmental quality requires that we examine a combination of diverse elements. Some of these elements are rather abstract from an analytical viewpoint. Even for the clearcut cases of highly toxic water pollutants, the losses and damages to natural systems are difficult to measure. So, for a subtler form of environmental impact such as lake drawdown, the evaluation of these estimates will be extremely subjective. Evaluation will differ greatly from planner to planner, depending on their perception of what the VOYA lake system's problems really are.

Two of the primary reasons cited for a general slacking off in the development of, and funding for, new multi-purpose reservoir projects in this country are: (1) that there is some concern about possible adverse environmental impacts of future projects, and (2) that there is a strong public desire to preserve remaining undeveloped areas in their natural state so as not to foreclose other possible uses in the future (Green and Eiker 1983). It is important for the National Park Service to consider the sorts of information contained in this report. It must determine if drawdown-related impacts to phytoplankton (as well as to all organisms which depend upon the aquatic resources of Voyageurs) impinge upon park goals and mandate as formulated in the enabling legislation of the park (Public Law 91-661, January 8, 1971)... ie., if it is, in fact, concerned with reason (2) as stated above.

Operation and maintenance activities of the Namakan Reservoir should attempt to maximize the stability of the system. It is suggested that the rule-curve be designed not to reduce adverse effects on recreational purposes, nor to provide high biological productivity of desirable species, nor to maximize power production at downstream facilities; but to most closely approximate projected "natural" (ie., undammed) conditions. Lake levels more similar to "natural" than present, will reduce bottom areas exposed by drawdown and accompanying sedimemt-water interactions, reduce die-off of littoral macrophytes and their accompanying nutrient inputs, reduce nutrient concentration effects due to volume changes, and minimize alteration of the aquatic habitat in general.

While average nutrient concentrations in mixed lakes may be of interest for preliminary water-quality management planning, temporally localized peak concentrations can cause fundamental changes in the ecology of entire lake systems (Loucks 1983). Model results predict that peak spring nutrient (TP) concentrations would be attenuated under "natural" fluctuation conditions in Kabetogama Lake (see Model Results). Keeping in mind that the model is uncalibrated and unconfirmed, it is predicted that the phytoplankton biomass and accompanying primary production would be reduced, though not extremely, under "natural" fluctuation conditions in Kabetogama Lake. This would have ramifications upward throughout the foodweb; on herbivorous zooplankton, planktiverous fish, pisciverous fish, etc. The possibility of reductions in primary production under a new, more "natural" lake level regime should be noted.

It is very difficult to define and quantify environmental quality and similar public policy objectives. Like most methods attempting to define and evaluate alternative water-level policies, the information obtained from quantitative techniques, such as those in this report, can only assist policy-makers, not replace them. This often leads to differences between the optimal solutions to water-quality management models and the eventual solution as chosen by the political process. This is why reservoir operating rules should be considered tentative. Though maximizing the stability of the VOYA lake system should be a primary goal, it should always be possible to improve the rules of Namakan Reservoir operation based upon experience.

Original objectives of the study which have not been met include: (1) determination of species composition, numbers and diversities of phytoplankton communities from preserved monthly samples, (2) determination of total phosphorus concentrations, (3) heavy metals analyses of a sample subset, originally hoped to be one sample per station. Additional objectives not realized during the 1986 field season, as stated in the 1985 Progress Report (Kepner and Stottlemyer 1986) include: (1) in situ measurement of remineralization of phosphorus and nitrogen from lake sedimemts, and (2) more complete data on solar radiation. These, perhaps overly-ambitious, objectives were not met due to time and budget limitations.

Literature Cited

American Public Health Association. 1980. Standard methods for the examination of water and wastewater. 15th edition. Washington, D.C., American Public Health Association, 1134 pp.

Anderl, W.H. 1976. Maintaining water quality in Voyageurs National Park. Preprint 2686. American Society of Civil Engineers.

Armstrong, F.A.J. and D.W. Schindler. 1971. Preliminary chemical characterization of waters in the Experimental Lakes Area, northwestern Ontario. J. Fish. Res. Bd. Canada 28: 171-187.

Arthur, C.R. and F.H. Rigler. 1967. A possible source of error in the ^{14}C method of measuring primary productivity. Limnol. Oceangr. 12: 121-124.

Barica, J. 1975. Collapses of algae blooms in prairie pothole lakes: their mechanism and ecological impact. Verh. Int. Verein. Limnol. 19: 606-615.

Beeton, A.M. and D.C. Chandler. 1963. The St. Lawrence Great Lakes, pp. 535-558. In: D.G. Frey [ed.] Limnology in North America., Univ. of Wisconsin Press, Madison, Wis.

Bierhuizen, J.F.H. and E.E. Prepas. 1985. Relationship between nutrients, dominant ions, and phytoplankton standing crop in prairie saline lakes. Can. J. Fish. Aquat. Sci. 42: 1588-1594.

Bower, P.M., C. Kelly, E. Fee, J. Shearer, D. DeClercq, and D. Schindler. 1987. Simultaneous measurement of primary production by whole-lake and bottle radiocarbon additions. Limnol. Oceangr. 32(2): 299-312.

Brunskill, G.J., D. Povoledo, B.W. Graham, and M.P. Stainton. 1971. Chemistry of surface sediments of sixteen lakes in the Experimental Lakes Area, northwestern Ontario. J. Fish Res. Bd. Canada 28: 277-294.

Brylinsky, M. and K.H. Mann. 1973. An analysis of factors governing productivity in lakes and reservoirs. Limnol. Oceangr. 18(1): 1-13.

Burnison, B.K. 1980. Modified dimethyl sulfoxide (DMSO) extraction for chlorophyll analysis of phytoplankton. Can. J. of Fish. Aquat. Sci. 37: 729-733.

Cabecadas, G. and M.J. Brogueira. 1987. Primary production and pigments in three low alkalinity connected reservoirs receiving mine wastes. Hydrobiologia 144: 173-182.

Canale, R.P. 1976. Modeling biochemical processes in aquatic ecosystems, Ann Arbor Science Publ., Ann Arbor, MI., pp. 76-78.

Carlson, R.E. 1977. A trophic state index for lakes. Limnol. Oceanogr. 22(2): 361-369.

Chevalier, J.R. 1977. Changes in walleye population and factors in abundance, 1924-75. J. Fish. Res. Bd. Canada. 34: 1696-1702.

Cullen, J.J., M. Zhu, and D.C. Pierson. 1986. A technique to assess the harmful effects of sampling and containment for determination of primary production. Limnol. Oceangr. 31(6): 1364-1373.

Dillon, P.J. and F.H. Rigler. 1974. The phosphorus-chlorophyll relationship in lakes. Limnol. Oceangr. 19: 767-773.

Dillon, P.J. and F.H. Rigler. 1975. A simple method for predicting the capacity of a lake for development based on lake trophic status. J. Fish. Res. Bd. Canada. 32: 1519-1531.

Duthie, H.C. 1968. Ecology of phytoplankton in Lake Belwood, a storage reservoir in southern Ontario. J. Fish. Res. Bd. Canada. 25(6): 1229-1245.

Eppley, R.W. 1982. The PRPOOS program: A study of plankton rate processes in oligotrophic oceans. Eos 163: 522-523.

Fahnenstiel, G.L. and D. Scavia. 1987. Dynamics of Lake Michigan phytoplankton: primary production and growth. Can. J. Fish. Aquat. Sci. 44: 499-508.

Fee, E.J. 1976. The vertical and seasonal distribution of chlorophyll in lakes of the Experimental Lakes Area, northwestern Ontario: Implications for primary production estimates. Limnol. Oceanogr. 21(6): 767-783.

Flett, R.J., D.W. Schindler, R.D. Hamilton, and N.E.R. Campbell. 1980. Nitrogen fixation in Canadian Precambrian Shield lakes. Can. J. Fish. Aquat. Sci. 37: 494-505.

Flug, M. 1986. Analysis of lake levels at Voyageurs National Park. Water Resources Div., National Park Service Report 86-5, 52 pp.

Gieskes, W.W., G.W. Kraay, and M.A. Baars. 1979. Current 14C methods for measuring primary production: Gross underestimates in oceanic waters. Neth. J. Sea Res. 2:109.127.

Goldich, S.S, A.O. Nier, H. Baadsgaard, H. Hoffman, and H. W. Krueger. 1961. The precambrian geology and geochronology of Minnesota. Minn. Geol. Survey Bull. 41, Univ. of Minnesota Press, Minneapolis, MN, 193 pp.

Goldman, C.R. 1960. Primary productivity and limiting factors in three lakes of the Alaska Peninsula. Ecol. Monogr. 30: 207-230.

Goldman, C.R. 1974. Eutrophication of Lake Tahoe emphasizing water quality. EPA-660/3-74-034. U.S. Government Printing Office, Washington, D.C., 408 pp.

Green, G.C. and E.E Eiker, Eds. 1983. Accomplishments and impacts of reservoirs. ASCE Water Resources Planning and Management Division symposium proceedings, 235 pp.

Gregor, D.J. and M.G. Johnson. 1980. Non-point source phosphorus inputs to the Great Lakes pp. 37-60 in Phosphorus management strategies for lakes, Ann Arbor Science Publ., Ann Arbor, MI.

Guseva, K.A. 1958. The influence of water level regime of the Rybinsk Reservoir on the development of phytoplankton. Tr. Biol. Sta. Borok. Akad. Nauk. SSR., 3: 112-124.

Hargis, J.R. 1981. Ecological analysis of the plankton communities of Voyageurs National Park. Final Report. USNPS contract no. CX-6000-8-R133, University of Minnesota-Duluth, 47 pp.

Hayes, F.R. and A.H. Anthony. 1964. Productive capacity of North American lakes as related to the quantity and the trophic level of fish, the lake dimensions, and the water chemistry. Trans. Amer. Fish. Soc. 93: 53-57.

Hodgkiss, I.J. and Y.C. Tai. 1976. Studies on Plover Cove Reservoir, Hong Kong, Part 3: A comparison of the species composition of diatom floras on different substrates and the effect of environmental factors on their growth. Freshwater Biology,. 6(3): 287-298.

Holm-Hansen, O. and B. Riemann. 1978. Chlorophyll-a determination: improvements in methodology. Oikos 30: 438-447.

Hutchinson, G.E. 1957. A treatise on limnology: I. Geography, Physics, and Chemistry. John Wiley & Sons, Inc., New York, NY. 1015 pp.

Johnson, M.G., M.F.P. Michalski, and A.E. Christie. 1969. Effects of acid mine wastes on phytoplankton in northern Ontario lakes. Ont. Water Res. Comm., Res. Publ. 30: 43 pp.

Jones, J.R. and R.W. Bachman. 1975. Algae responses to nutrient inputs in some Iowa lakes. Verh. Int. Verein. Limnol. 19: 904-910.

Kalff, J. and E. Bentzen. 1984. A method for the analysis of total nitrogen in natural waters. Can. J. Fish. Aquat. Sci. 41: 815-819.

Kallemeyn, L.W., M.H. Reiser, D.W. Smith and J.M. Thurber. 1987. Effects of regulated lake levels on the aquatic ecosystem of Voyageurs National Park. (in press).

Kepner, R. and R. Stottlemyer. 1986. Comprehensive determination of physical and chemical factors effecting primary production in the Voyageurs National Park lake system. GLARSU Tech. Rept. #18 (progress report) submitted to NPS, Omaha, NE, 82 pp.

Kraft, K.J. 1986. The effect of unnatural water level fluctuations on benthic invertebrates in Voyageurs National Park. Final Report. USNPS cooperative agreement no. CA-6000-4-8003, 21 pp.

Kwiatkowski, R.E. and J.C. Roff. 1976. Effects of acidity on the phytoplankton and primary productivity of selected northern Ontario lakes. Can. J. Bot. 54: 2546- 2561.

Likens, G.E., F.H. Bormann, N.M. Johnson, and R.S.Pierce. 1967. The calcium, magnesium, potassium, and sodium budgets for a small forested ecosystem. Ecology 48: 772-785.

Likens, G.E. [Ed.]. 1985. An ecosystem approach to aquatic ecology, Mirror Lake and its environment. Springer-Verlag New York, Inc., 516 pp.

Lind, O.T. 1979. Handbook of common methods in limnology. C.V. Mosby Company, St. Louis, MO. 199 pp.

Livingstone, D.A. 1963. Chemical composition of rivers and lakes. Chap G. Data of Geochemistry 6th ed. Prof. Pap. U.S. Geol. Surv., 440-G, 64 pp.

Meeks, J.C. 1974. Chlorophylls. Ch. 5 in Botanical Monographs Vol. 10: Algal physiology and biochemistry. ed. W.D.P. Stewart, University of California Press, Berkeley and Los Angeles, CA., pp. 161-168.

Megard, R.O. 1972. Phytoplankton, photosynthesis, and phosphorus in Lake Minnetonka, Minnesota. Limnol. Oceangr. 17: 68-87.

Megard, R.O. and P.D. Smith. 1974. Mechanisms that regulate growth rates of phytoplankton in Shagawa Lake, Minnesota. Limnol. Oceangr. 19(2): 279-296.

Miller, M.C., G.R. Hater, P. Spatt, P. Westlake, and D. Yeakel. 1986. Primary production and its control in Toolik Lake, Alaska. Arch. Hydrobiol./Suppl. 74(1): 97-131.

Minnesota Geological Survey. 1969. The proposed Voyageurs National Park: Its geology and mineral potential. Univ. of Minnesota, Minneapolis, MN, 16 pp.

Mitchell, S.F. 1975. Some effects of agricultural development and fluctuations in water level on the phytoplankton and zooplankton of a New Zealand reservoir. Freshwater Biology, 5(6): 547-562.

Nalewajko, C. 1966. Photosynthesis and excretion in various planktonic algae. Limnol. Oceangr. 11: 1-10.

National Oceanographic and Atmospheric Administration. 1985. Climatological data national summary: annual summary, Vol. 91 (13), NOAA. National Climatic Center, Asheville, NC.

National Oceanographic and Atmospheric Administration. 1986. Climatological data national summary: annual summary, Vol. 92 (13), NOAA. National Climatic Center, Asheville, NC.

National Park Service. 1973. Resources basic inventory - primary development areas, Voyageurs Natl. Park, MN., Report No. 1. USNPS contract no. CX-4000-3-0057, Univ. of Minnesota, 367 pp.

National Research Council. 1986. Acid deposition long-term trends. Washington, D.C.: National Academy Press, 506 pp.

Nelson-Jameson, B., D. Rutkowski, and R. Stottlemyer. 1986. Assessing anthropogenic atmospheric deposition effects in national parks of the Great Lakes Basin. GLARSU Tech. Rept. #16 (final report) submitted to NPS, Omaha, NE, 81 pp.

Northcote, T.C. and P.A. Larkin. 1956. Indices of productivity in British Columbia lakes. J. Fish. Res. Bd. Canada. 13: 515-540.

Oglesby, R.T. 1977. Phytoplankton summer standing crop and annual productivity as functions of phosphorus loading and various physical factors. J. Fish. Res. Bd. Can. 34: 2255-2270.

Oglesby, R.T. and W.R. Schaffner. 1978. Phosphorus loadings to lakes and some of their responses. Part 2, Regression models of summer phytoplankton standing crops, winter total P, and transparency of New York lakes with known phosphorus loadings. Limnol. Oceangr. 23: 135-145.

Ojakangas, R.W. 1970. Geology of a greenstone belt in Minnesota: Rainy Lake to Lake of the Woods [abs.] Institute on Lake Superior Geology, Proceedings 16th Annual Meeting, Thunder Bay, Ontario, pp. 32-34.

Ojakangas, R.W. 1972. Rainy Lake Area. In: Sims, P.K. and G.B. Morey [eds.], Geology of Minnesota: A centennial volume. Minn. Geol. Survey, Univ. of Minnesota Press, Minneapolis, MN, pp. 163-171.

Ojakangas, R.W. and C.L. Matsch. 1982. Minnesota's Geology. Univ. of Minnesota Press, Minneapolis, MN, pp. 191-197.

Ostrofsky, M.L. and F.H. Rigler. 1987. Chlorophyll - phosphorus relationships for subarctic lakes in western Canada. Can. J. Fish. Aquat. Sci. 44: 775-781.

Otsuki, A. and R.G. Wetzel. 1974. Calcium and total alkalinity budgets and calcium carbonate precipitation of a small hard-water lake. Arch. Hydrobiol. 73: 14-30.

Ownbey, C.R. and D.A. Kee. 1967. Chlorides in Lake Erie. Proc. Conf. Great Lakes Res., Int. Assoc. Great Lakes Res. 10: 382-389.

Payne, G.A. 1978. Water-quality reconnaissance of lakes in Voyageurs National Park, Minnesota. Administrative Report, U.S. Department of the Interior Geological Survey, St. Paul, MN.

Premo, B.J., C.D. McNabb, F.C. Payne, T.R. Batterson, J.R. Craig, and M. Siami. 1985. Predicting concentration of total phosphorus and chlorophyll-a in a lake with short hydraulic residence time. Hydrobiologia 122: 231-241.

Prepas, E.E. and D.O. Trew. 1983. Evaluation of the phosphorus - chlorophyll relationship for lakes off the Precambrian Shield in western Canada. J. Fish. Aquat. Sci. 40: 27-35.

Prescott, G.W. 1960. Biological disturbances resulting from algae populations in standing water. In: The Ecology of Algae. Spec. Pub. #2, Pymatuning Laboratory of Field Biology, University of Pittsburgh, pp. 22-37.

Pridmore, R.D., W.N. Vant and J.C. Rutherford. 1985. Chlorophyll - nutrient relationships in North Island lakes. Hydrobiologia 121: 181-189.

Rawson, D.S. 1952. Mean depth and the fish production of large lakes. Ecology. 33: 515-521.

Rawson, D.S. 1953. The standing crop of net-plankton in lakes. J. Fish. Res. Bd. Canada. 10: 224-237.

Rawson, D.S. 1955. Morphometry as a dominant factor in the productivity of large lakes. Verh. Int. Ver. Limnol. 12: 164-175.

Rawson, D.S. 1956. Algal indicators of trophic lake types. Limnol. Oceanogr. 1: 18-25.

Reckhow, K.H. and S.C. Chapra. 1983. Engineering approaches for lake management, Volume 1: Data analysis and empirical modeling. Butterworth Publishers, Boston, MA, 340 pp.

Rigler, F.H. 1964. The phosphorus fractions and the turnover time of inorganic phosphorus in different types of lakes. Limnol. Oceangr. 9: 511-518.

Ryding, S.O. [Ed.] 1980. Monitoring of inland waters. OECD eutrophication programme, the Nordic project. NORDFORSK, Helsinki, Finland.

Sager, P.E., G. Banta, and J. Kirk. 1984. The relation between areal and volumetric expressions of ^{14}C productivity in Green Bay, Lake Michigan. Verh. Int. Limnol. 22: 470-474.

Sakamoto, M. 1966. Primary production by phytoplankton communities in some Japanese lakes and its dependence on lake depth. Arch Hydrobiol. 62: 1-28.

Saunders, G.W., F.B. Trama, and R.W. Bachmann. 1965. Evaluation of a modified ^{14}C technique for estimation of photosynthesis in large lakes. Great Lakes Research Division, Institute of Science and Technology, University of Michigan, Ann Arbor, Michigan. 61 pp.

Schindler, D.W. 1971. Carbon, nitrogen, and phosphorus and the eutrophication of freshwater lakes. J. Phycol. 7: 321-329.

Schindler, D.W. 1971. A hypothesis to explain differences and similarities among lakes in the ELA, N.W. Ontario. J. Fish. Res. Bd. Canada. 28: 295-301.

Schindler, D.W. 1975. Whole-lake eutrophication experiments with phosphorus, nitrogen, and carbon. Verh. Int. Ver. Limnol. 19: 3221-3231.

Schindler, D.W. 1977. Evolution of phosphorus limitation in lakes. Science 195: 260-262.

Schindler, D.W. and J.E. Nighswander. 1970. Nutrient supply and primary production in Clear Lake, Eastern Ontario. J. Fish. Res. Bd. Canada. 27 (1): 2009-2036.

Schindler, D.W. and S.K. Holmgren. 1971. Primary production and phytoplankton in the ELA, N.W. Ontario, and other low-carbonate waters, and a liquid scintillation method for determining ^{14}C activity in photosynthesis. J. Fish. Res. Bd. Canada 28: 189-201.

Schwartz, G.M. and G.A. Thiel. 1963. Minnesota's rocks and waters: A geological story, rev. ed., Minn. Geol. Survey Bull. 37, Univ. of Minnesota Press, Minneapolis, MN, 366 pp.

Serruya, C.E. and U. Pollingher. 1977. Lowering of water level and algal biomass in Lake Kinneret. Hydrobiologia, 54(1): 73-80.

Shaw, B.H., J.F. Sullivan, and J.G. Vennie. 1981. The impact of agricultural runoff and reservoir drawdown on the Big Eau Pleine Reservoir, Wisconsin. Paper No. 4-18 in Surface Water Impoundments, pp. 345-359.

Silva, E.I.L. and R.W. Davies. 1986. Primary productivity and related parameters in three different types of inland waters in Sri Lanka. Hydrobiol. 137: 239-249.

Smith, V.H. 1983. Low nitrogen to phosphorus ratios favor dominance by blue-green algae in lake phytoplankton. Science 221: 665-671.

Southwick, D.L. and R.W. Ojakangas. 1979. Geologic map of Minnesota, International Falls sheet. Minn. Geol. Survey, scale 1:250,000.

Spacie, A. and J.M. Bell. 1980. Trophic status of fifteen Indiana lakes in 1977. Ag. Exp. Sta. Report RB 966, Purdue University, 54 pp.

Steemann-Nielsen, E. 1952. The use of radioactive carbon (^{14}C) for measuring organic production in the sea. J. Cons. Int. Expl. Mer 18:117-140.

Stockner, J.G. and K.S. Shortreed. 1984. Whole-lake fertilization experiments in coastal British Columbia lakes: empirical relationships between nutrient inputs and phytoplankton biomass and production. Can. J. Fish. Aquat. Sci. 42: 649-658.

Stottlemyer, R. 1987. Monitoring and quality assurance procedures for the study of remote watershed ecosystems. In: New approaches to monitoring aquatic ecosystems, American Society of Testing Materials, Philadelphia, PA., pp. 189-198.

Strickland, J.D. and T.R. Parsons. 1972. A practical handbook of seawater analysis, 2nd Ed., Fish. Res. Bd. Can., Ottawa, Can., 310 pp.

Sullivan, J.F. 1978. Primary production of the Big Eau Pleine Reservoir, Wisconsin. M.S. Thesis. University of Wisconsin-Stevens Point, 141 pp.

Thomas, J.F.J. 1959. Nelson River drainage basin in Canada, 1953-56. Ind. Water Res. Can., Water Surv. Rept. 9. Can. Dep. Mines Tech. Surv., Mines Br., 147 pp.

Tundisi, J.G. 1983. A review of basic ecological processes interacting with production and standing-stock of phytoplankton in lakes and reservoirs of Brazil. Hydrobiologia, 100: 223-243.

USEPA. 1983. Methods for chemical analysis of water and wastes. EPA-600/4-79-020. USEPA, Cincinnati, OH.

USEPA. 1986. Characteristics of lakes in the eastern U.S., Volume III: Data compendium of site characteristics and chemical variables. Office of Research and Development, Washington, DC., EPA/600/4-86/007c. p 194.

Vanderhoef, L.N., Huang, C.Y., and R. Musil. 1974. Nitrogen fixation (acetylene reduction) by phytoplankton in Green Bay, Lake Michigan, in relation to nutrient concentrations. Limnol. Oceangr. 19: 119-125.

Vennie, J.G. and B.H. Shaw. 1979. Agricultural runoff and reservoir drawdown effects on nutrient dynamics of a eutrophic reservoir. Paper presented at the 1979 N. Amer. Lake Mgmt. Conf., April 16-18, 1979.

Vollenweider, R.A. 1965. Calculation models of photosynthesis-depth curves and some implications regarding day rate estimates in primary production measurements. Mem. Ist. Ital. Hydrobiol. 18 Suppl.: 425-457.

Vollenweider, R.A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication . OECD Report no. DAS/CSI/68.27, In: Wetzel, R.G. 1975. Limnology. W.B. Saunders Company, Philadelphia, PA. p. 242.

Wetzel, R.G. 1975. Limnology. W.B. Saunders Company, Philadelphia, PA. 743 pp.

Wetzel, R.G. and G.E. Likens. 1979. Limnological analyses. W.B. Saunders Company, Philadelphia, PA. 357 pp.

Williams, P.J., L.T. Berman and O. Holm-Hansen. 1972. Potential sources of error in the measurement of low rates of planktonic photosynthesis and excretion. Nature 236: 91-92.

Zumberge, J.H. 1952. The lakes of Minnesota: their origin and classification. Minnesota Geological Survey, Bulletin 35: Univ. of Minnesota, St. Paul, MN. 99 pp.

APPENDIX A

Table of conversion factors and equivalent weights.

Ion	Equivalent Weight	Factor*
Cl^-	35.46	28.2
NO_3^-	62.01	16.1
SO_4^{-2}	48.03	20.8
PO_4^{-3}	96.98	10.3
HCO_3^-	61.00	16.4
H^+	1.01	990.1
NH_4^+	18.04	55.4
Na^+	22.99	43.5
K^+	39.10	25.6
Mg^{+2}	12.15	82.3
Ca^{+2}	20.04	49.9
Si^{+4}	7.02	142.4

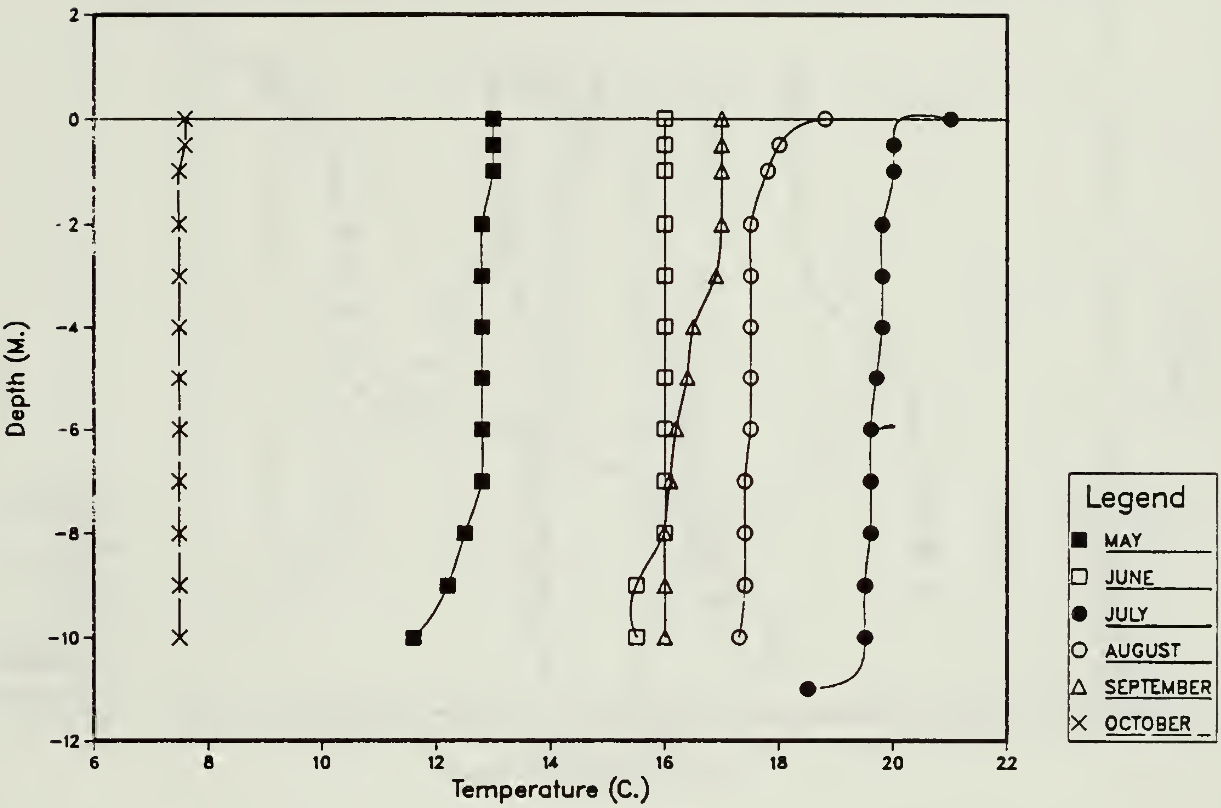
* mg/L = (μeq/L)/Factor ; μeq/L = (mg/L) x Factor

Appendix B

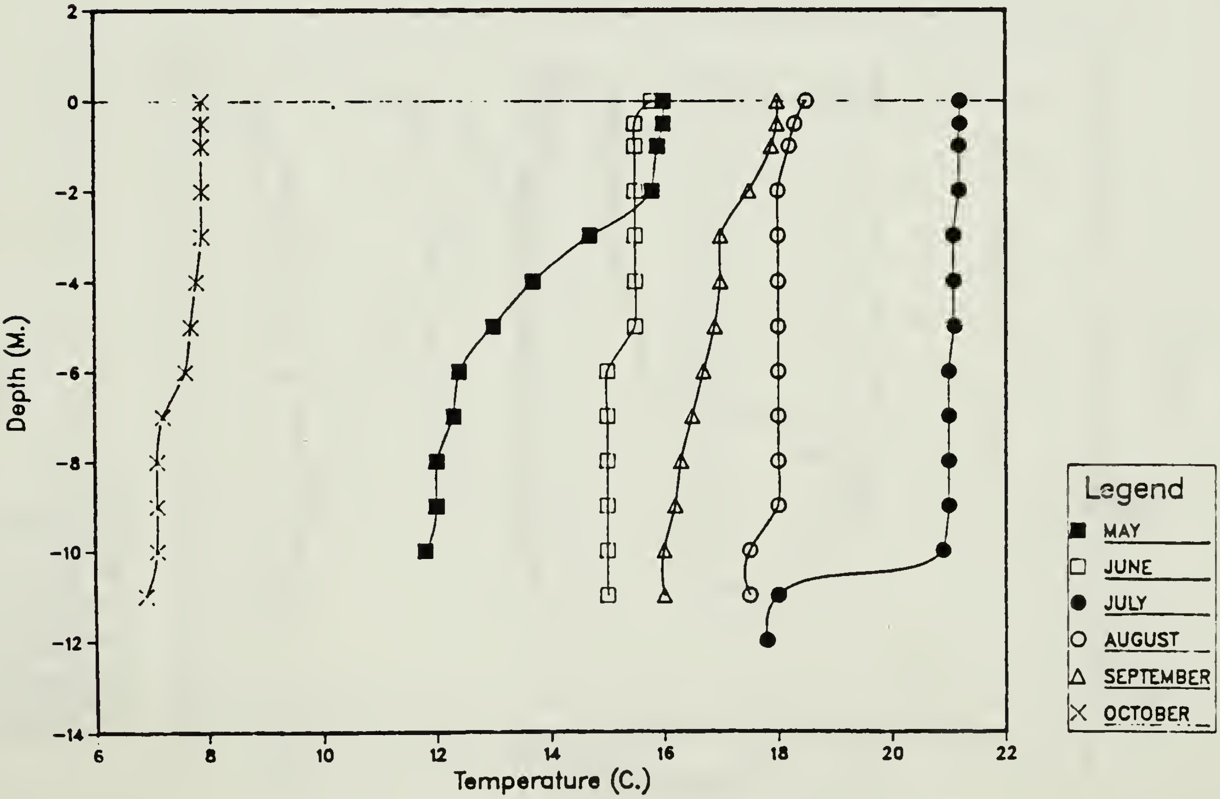
Monthly temperature profiles for the eight main lake sampling staions during the 1985 field season, Voyageurs National Park, MN.

Monthly Temperature Profiles

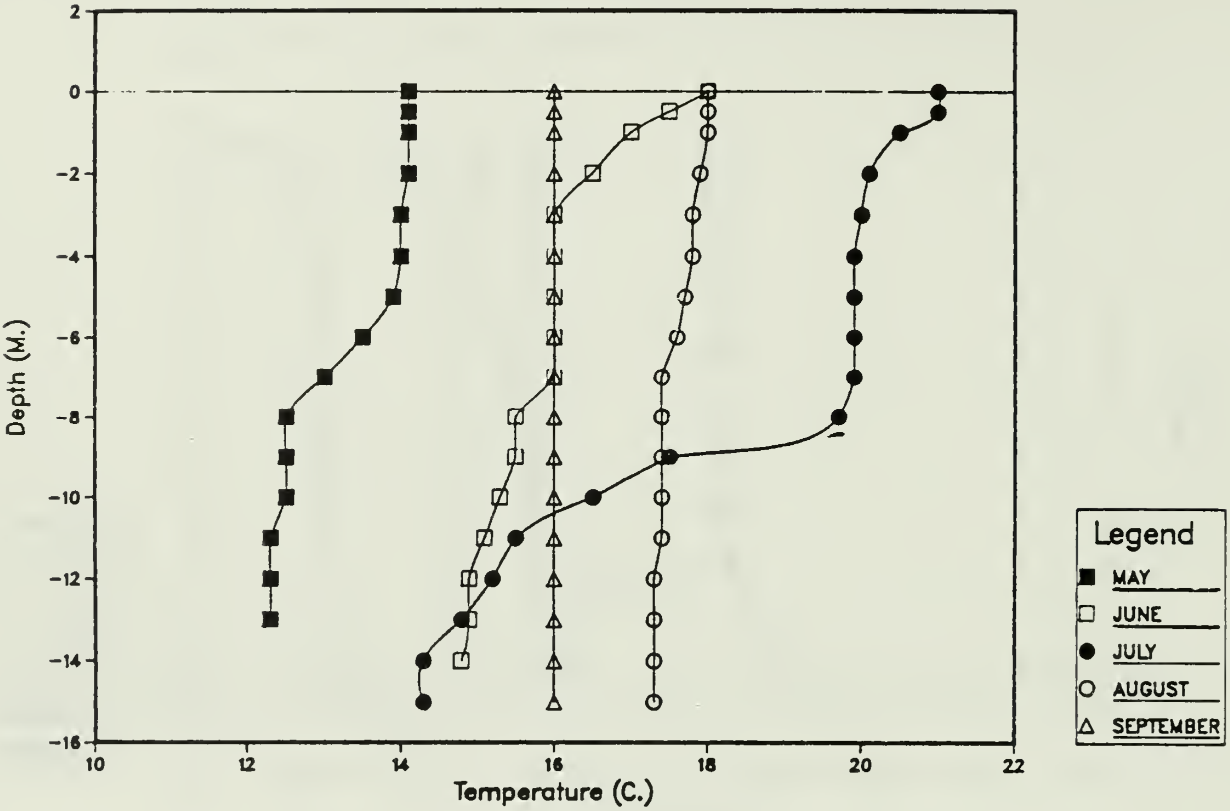
Station KA



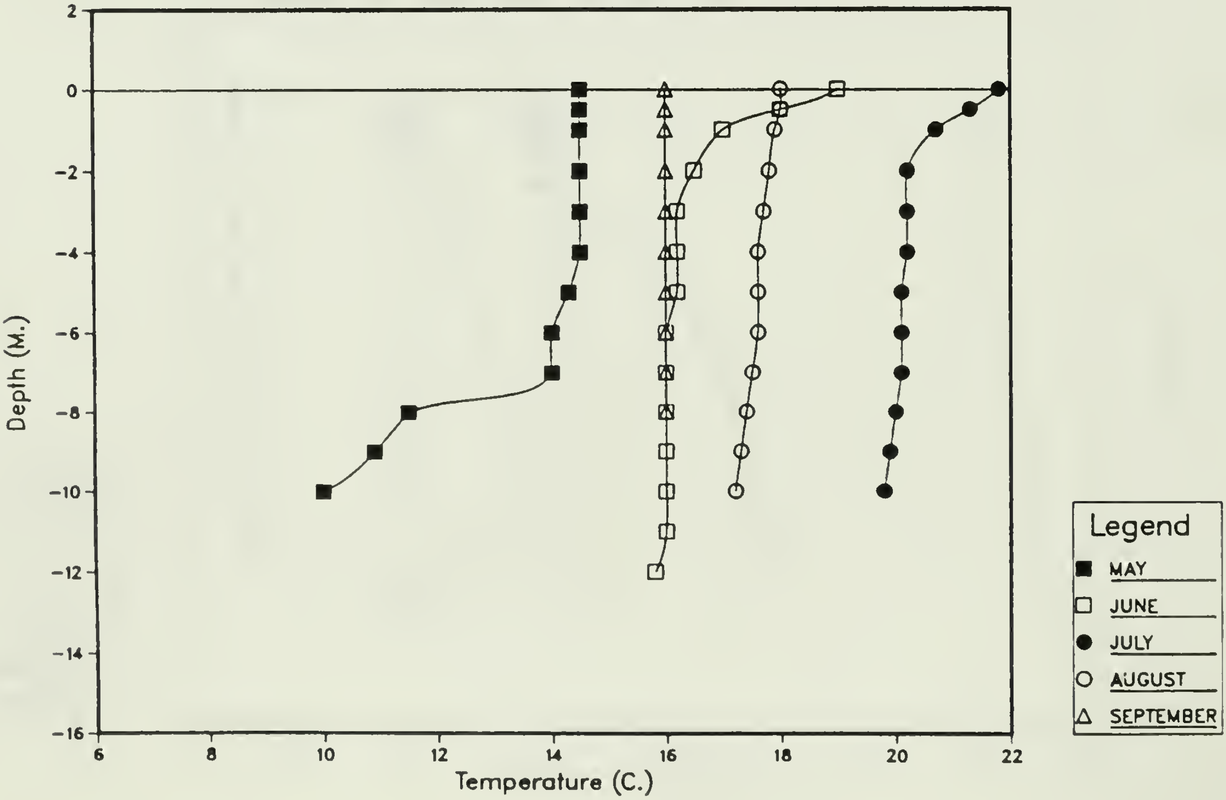
Station KB



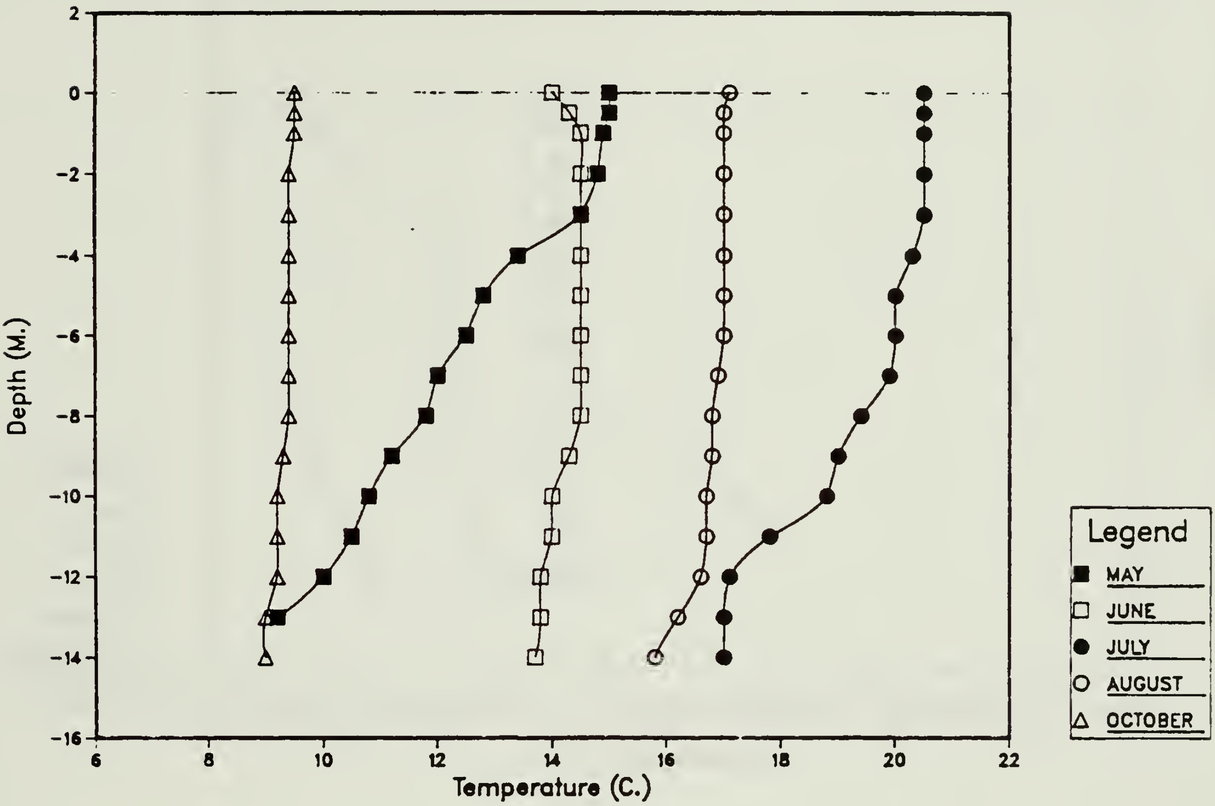
Monthly Temperature Profiles
Station NA



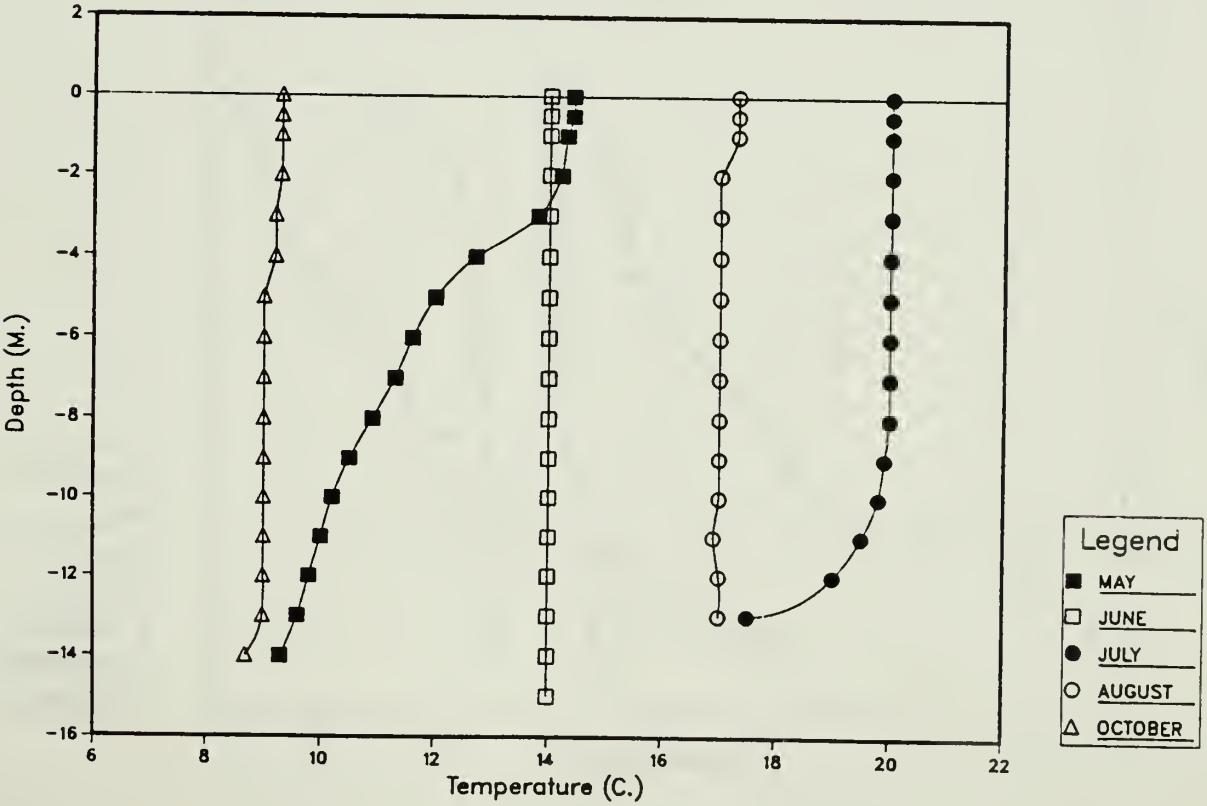
Station NB



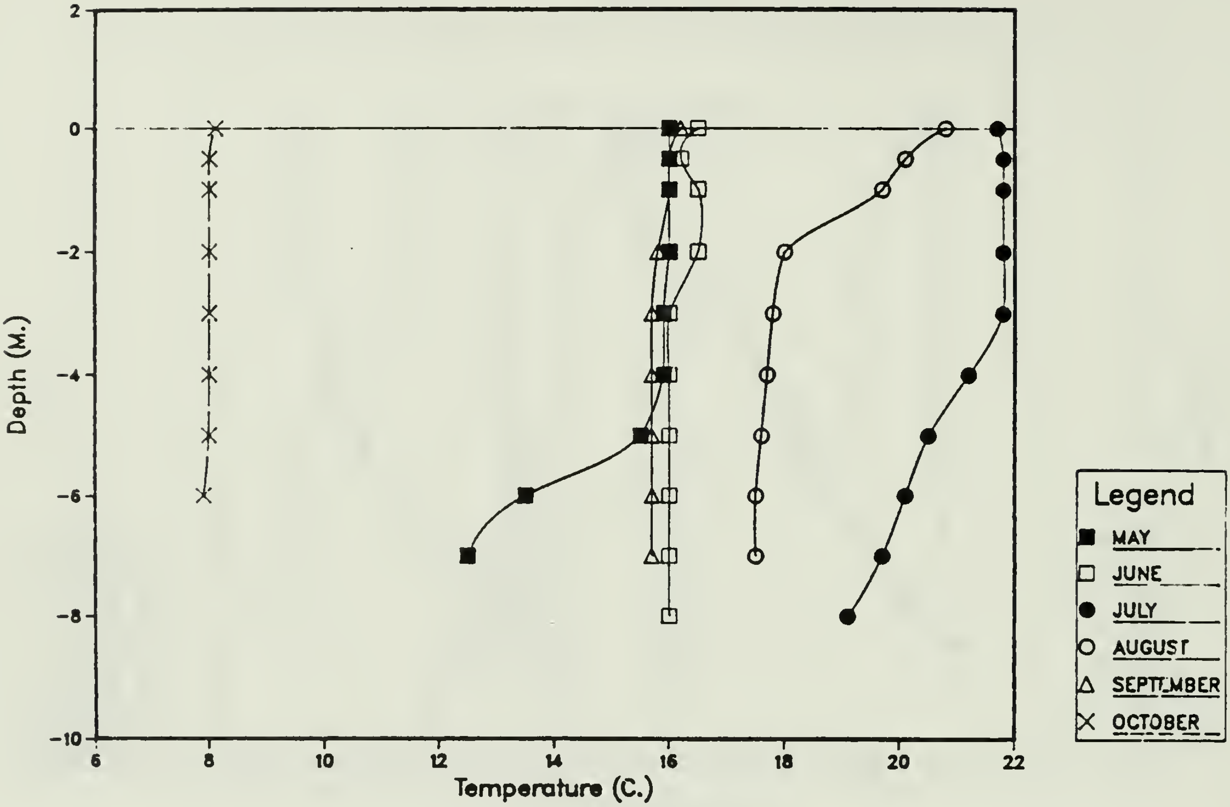
Monthly Temperature Profiles
Station RA



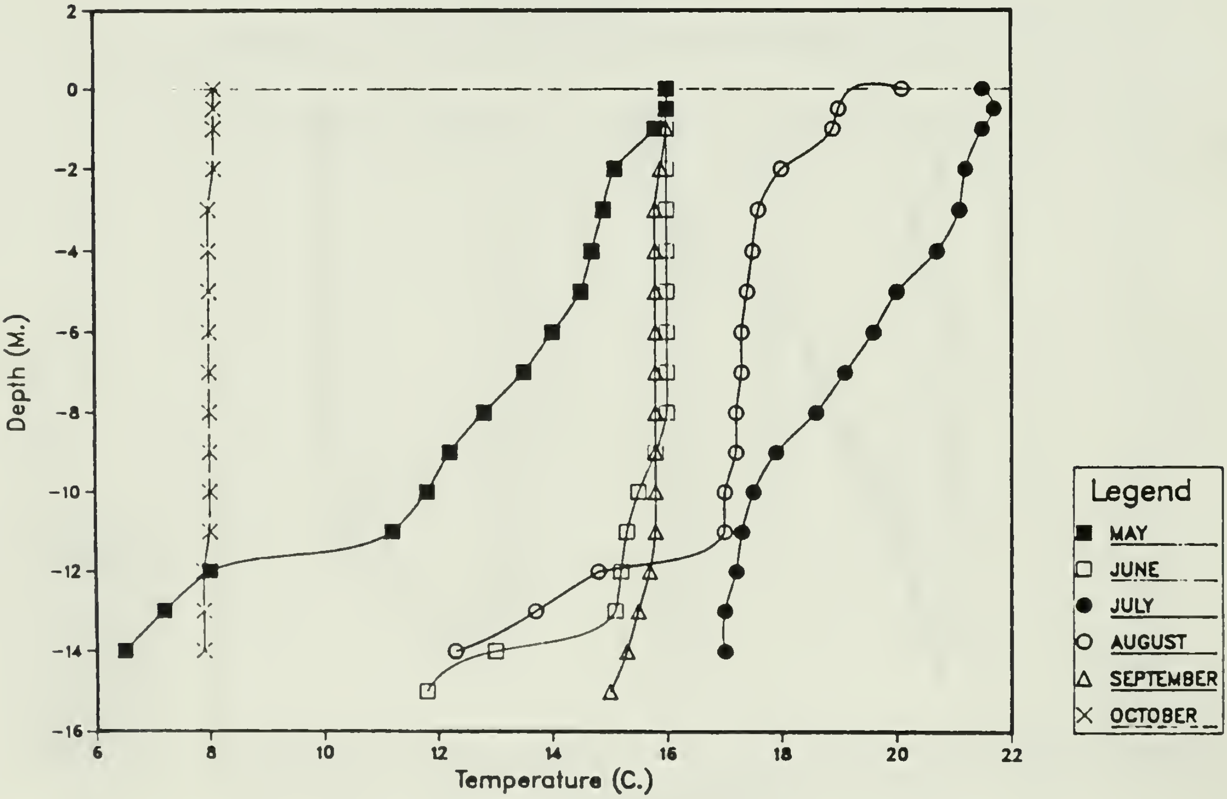
Station RB



Monthly Temperature Profiles
Station GB



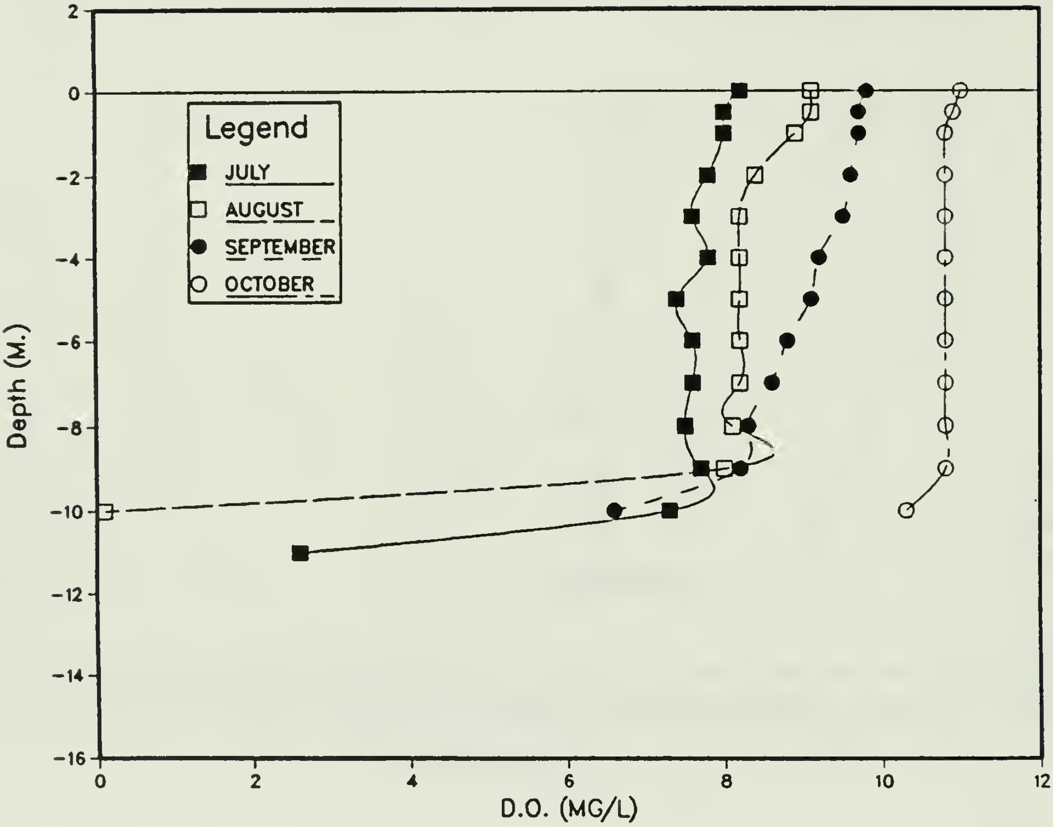
Station SP



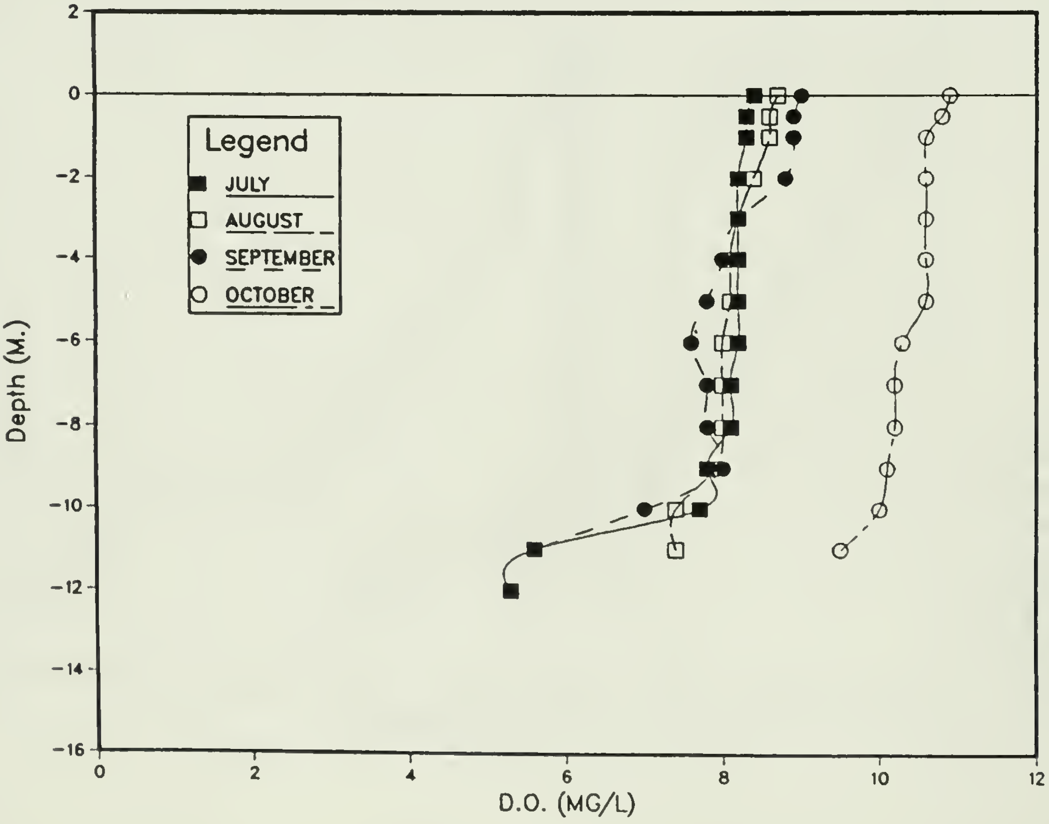
Appendix C

Monthly dissolved oxygen profiles (mg L^{-1}) for the eight main lake sampling stations during 1985, Voyageurs National Park, MN.

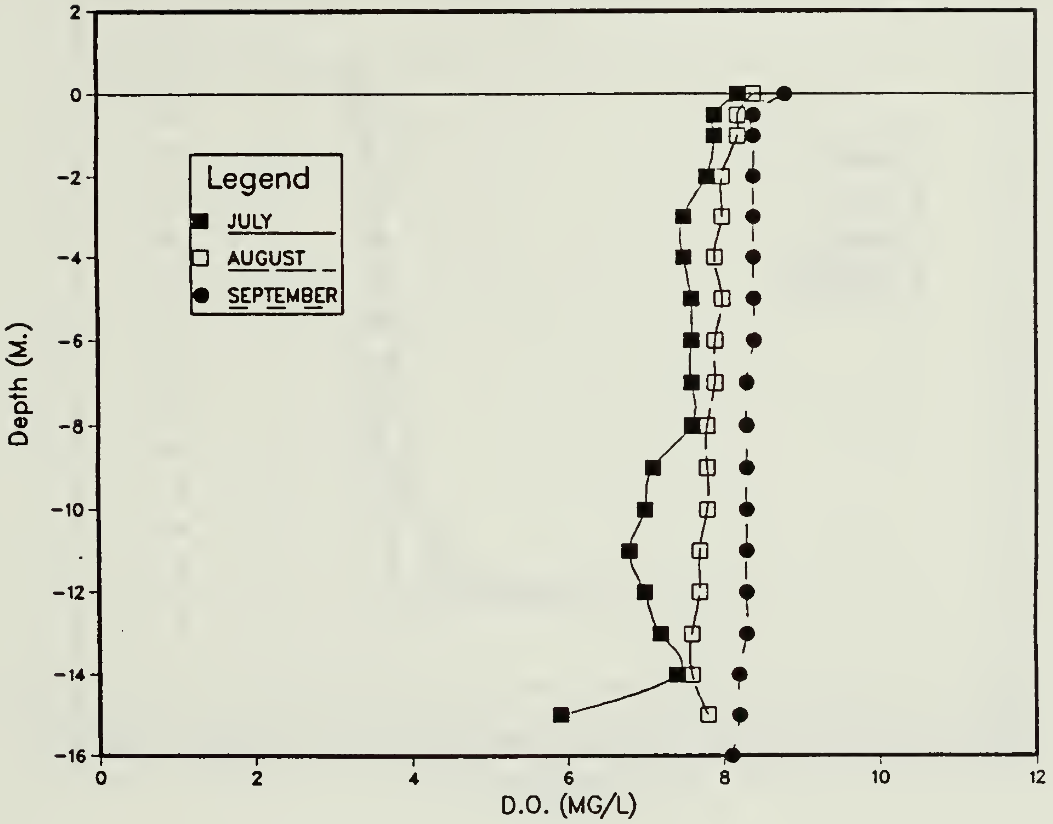
Monthly Dissolved Oxygen Profiles
Station KA



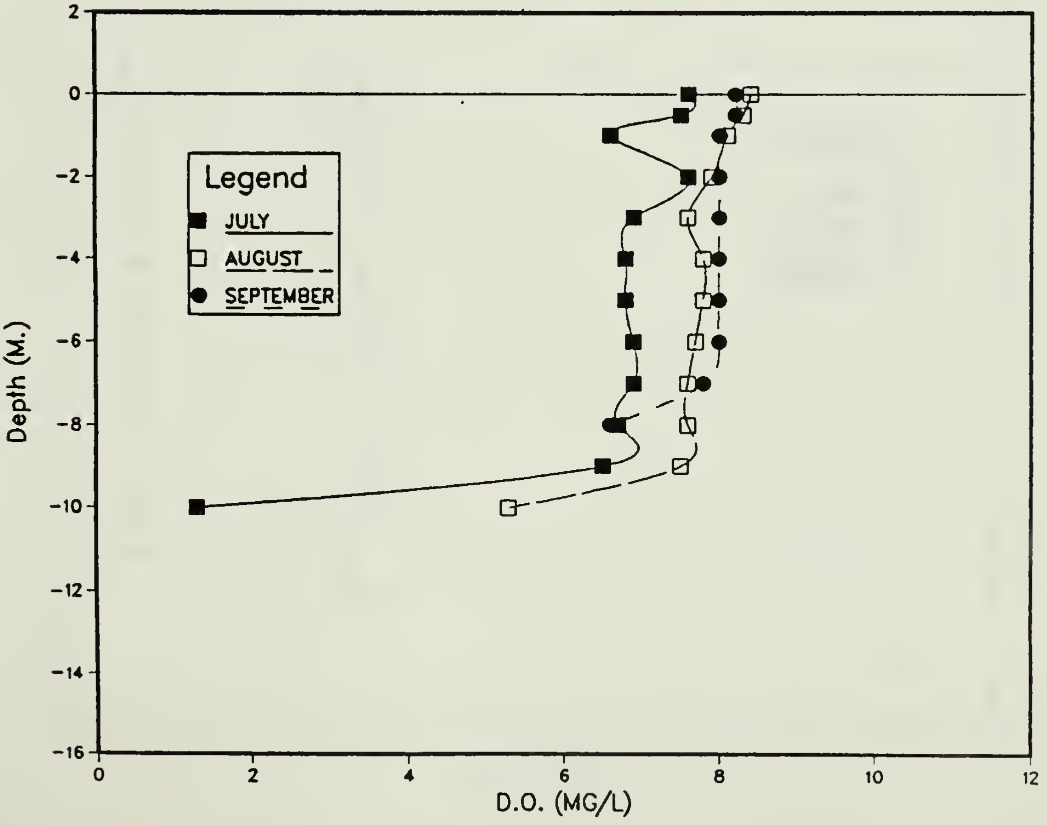
Station KB



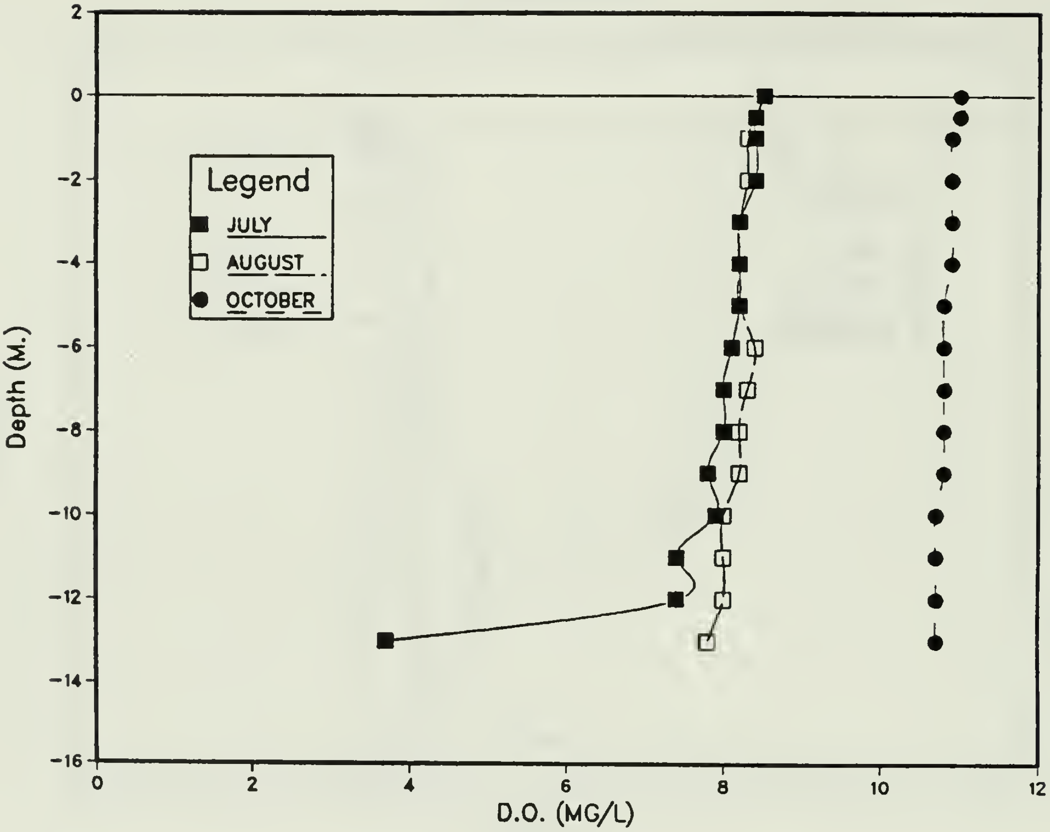
Monthly Dissolved Oxygen Profiles
Station NA



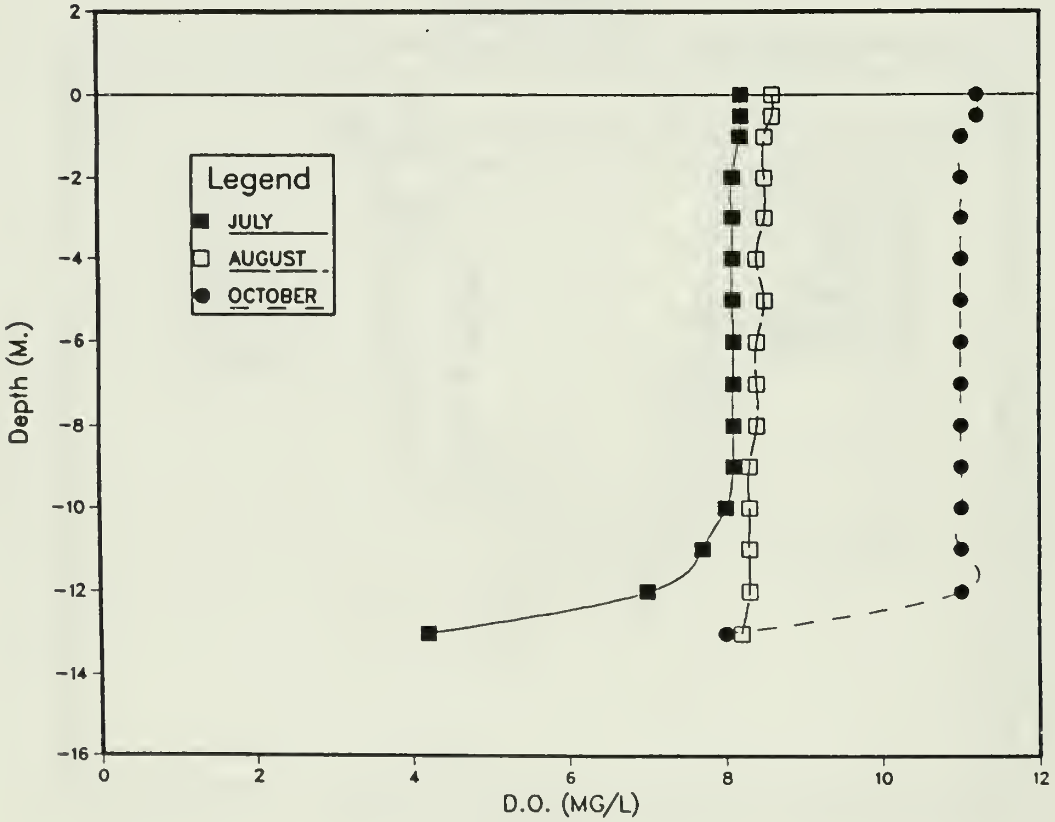
Station NB



Monthly Dissolved Oxygen Profiles
Station RA



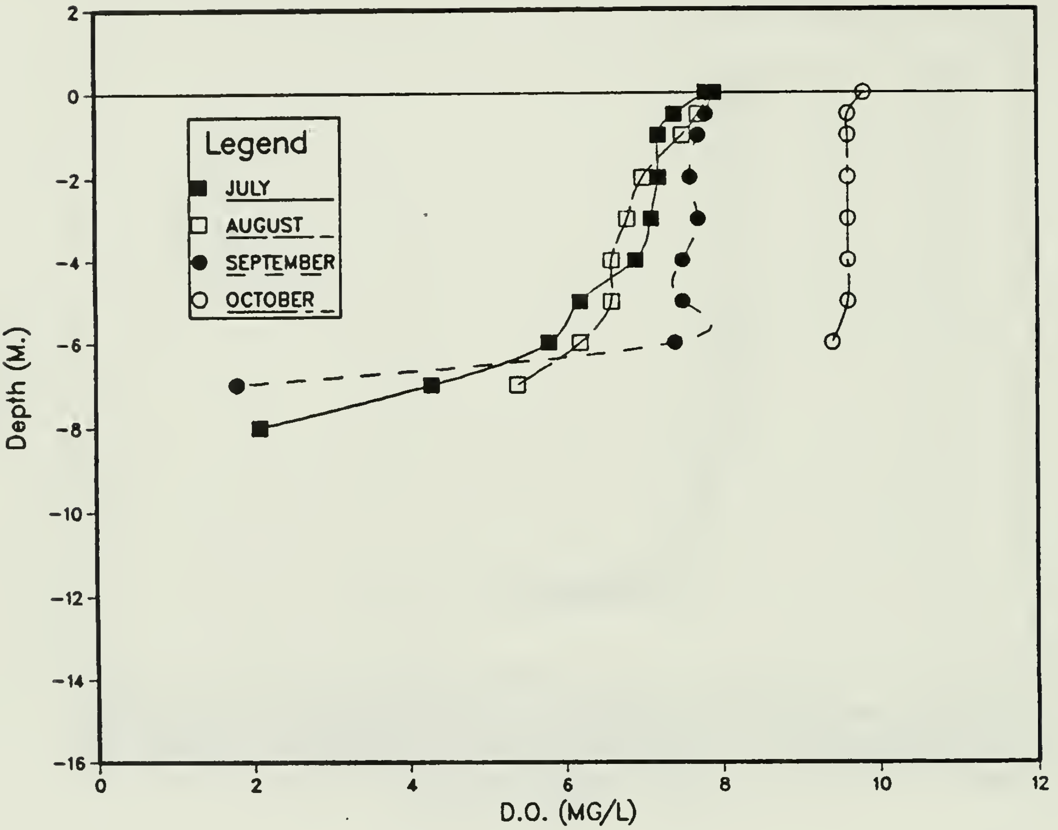
Station RB



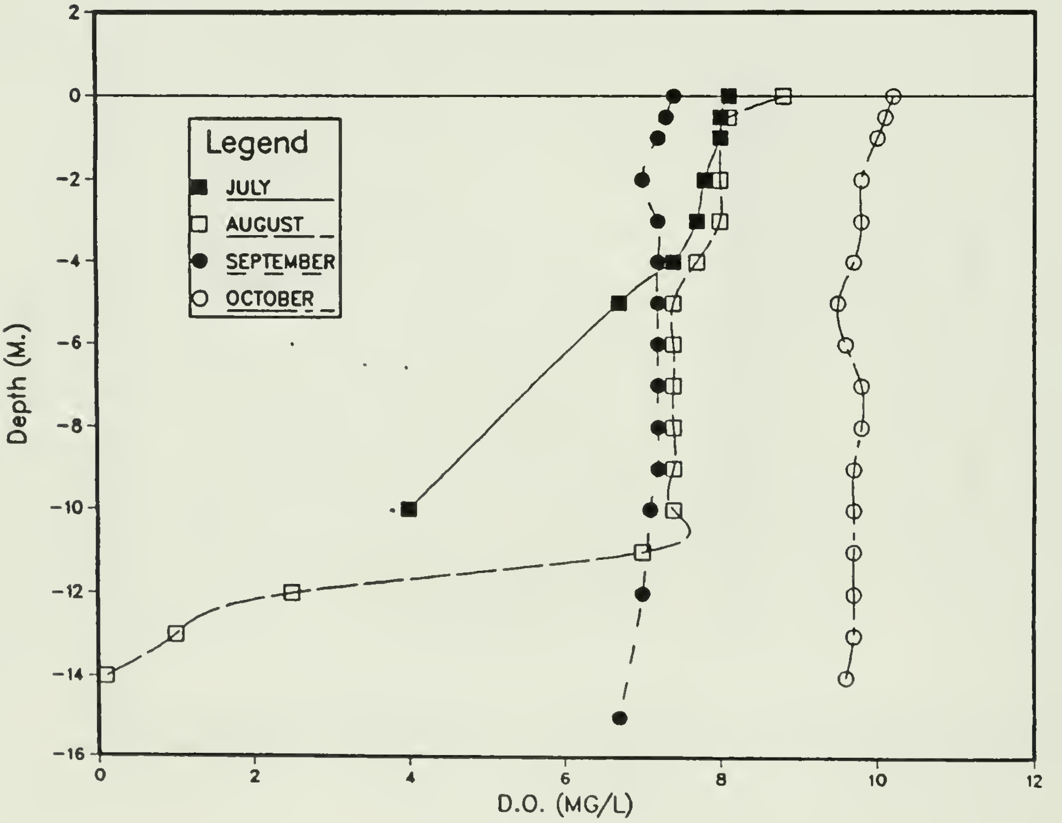
Appendix D

Mean monthly photosynthetic photon flux density (PPFD) in µEinst sec^{-1} m^{-2} for each of the eight main lake sampling stations, May 1985 thru October 1986, Voyageurs National Park, MN. Means of measurements take at 1 m above water surface, surface, 0.5, 1, 2, 3, 4, and 5 m below surface.

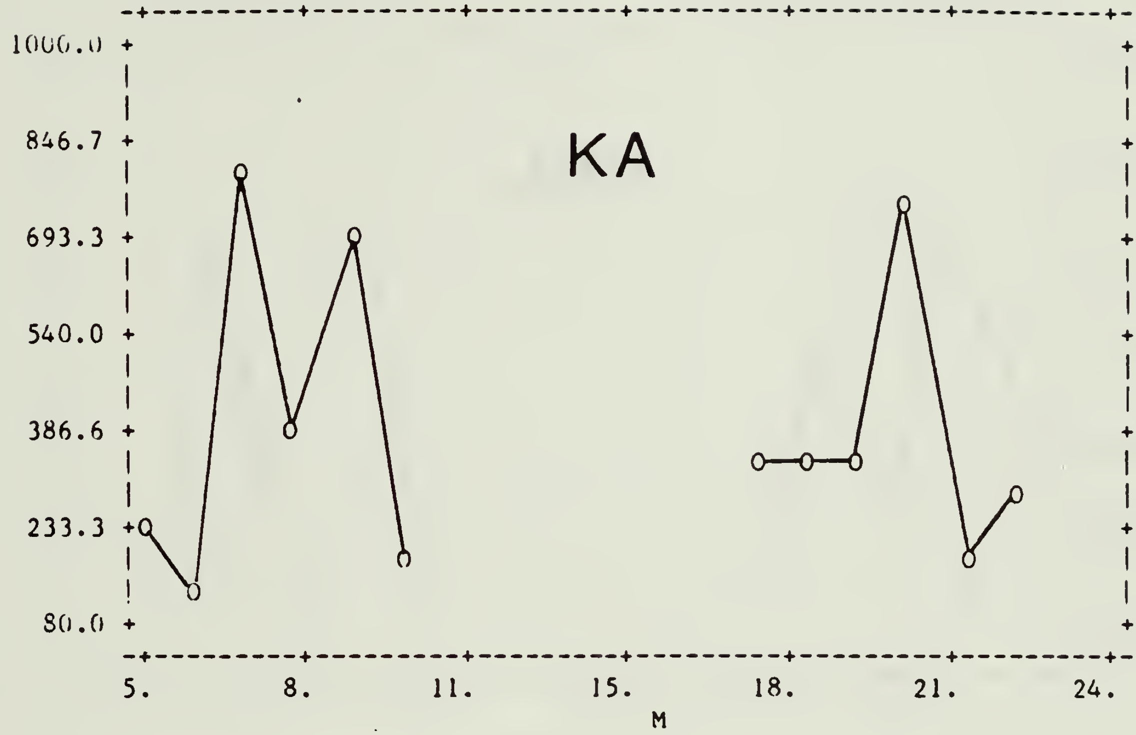
Monthly Dissolved Oxygen Profiles
Station GB



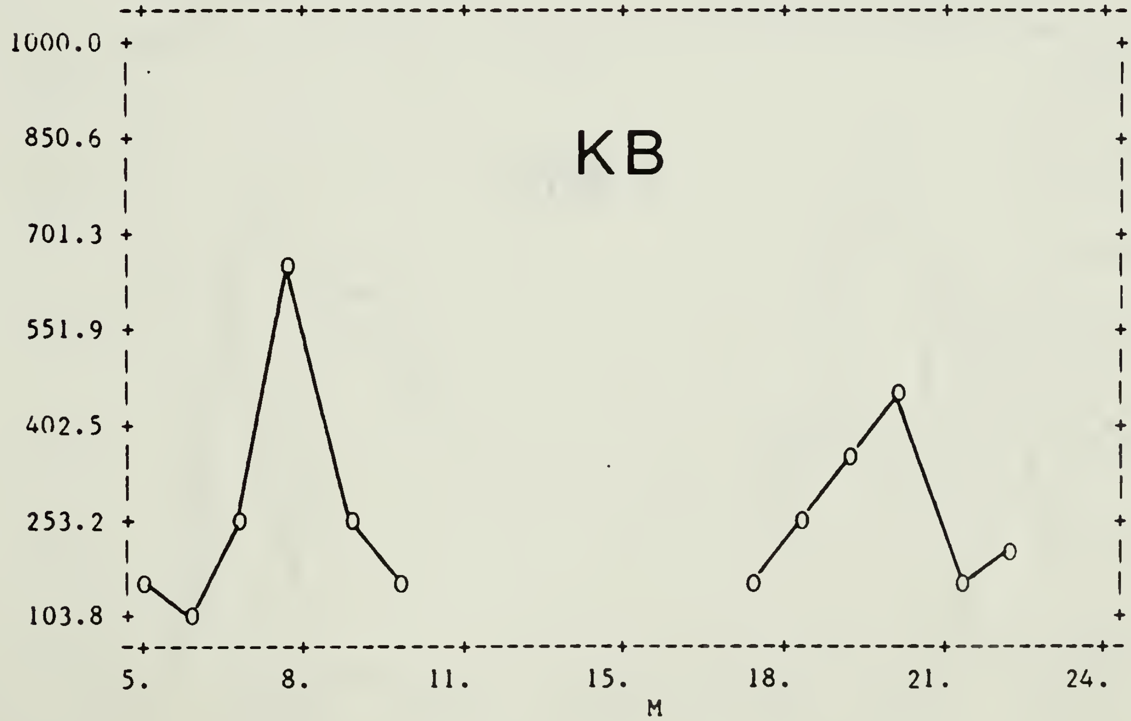
Station SP

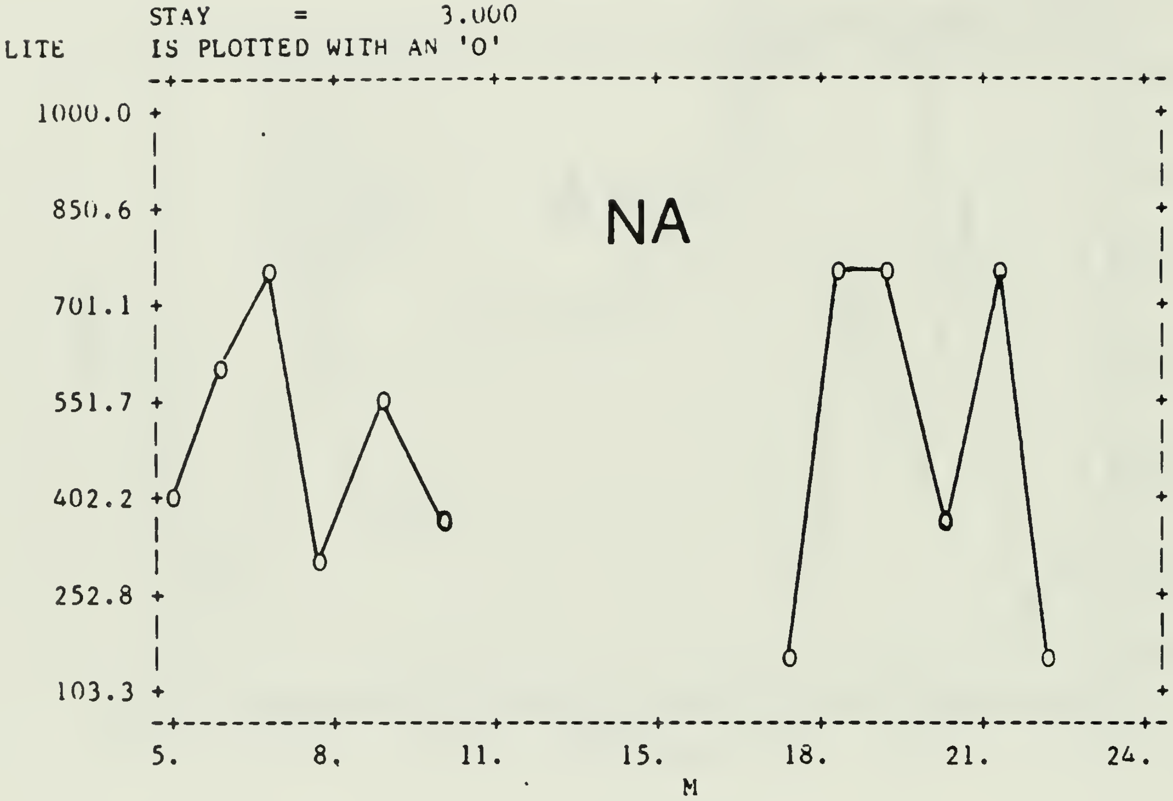


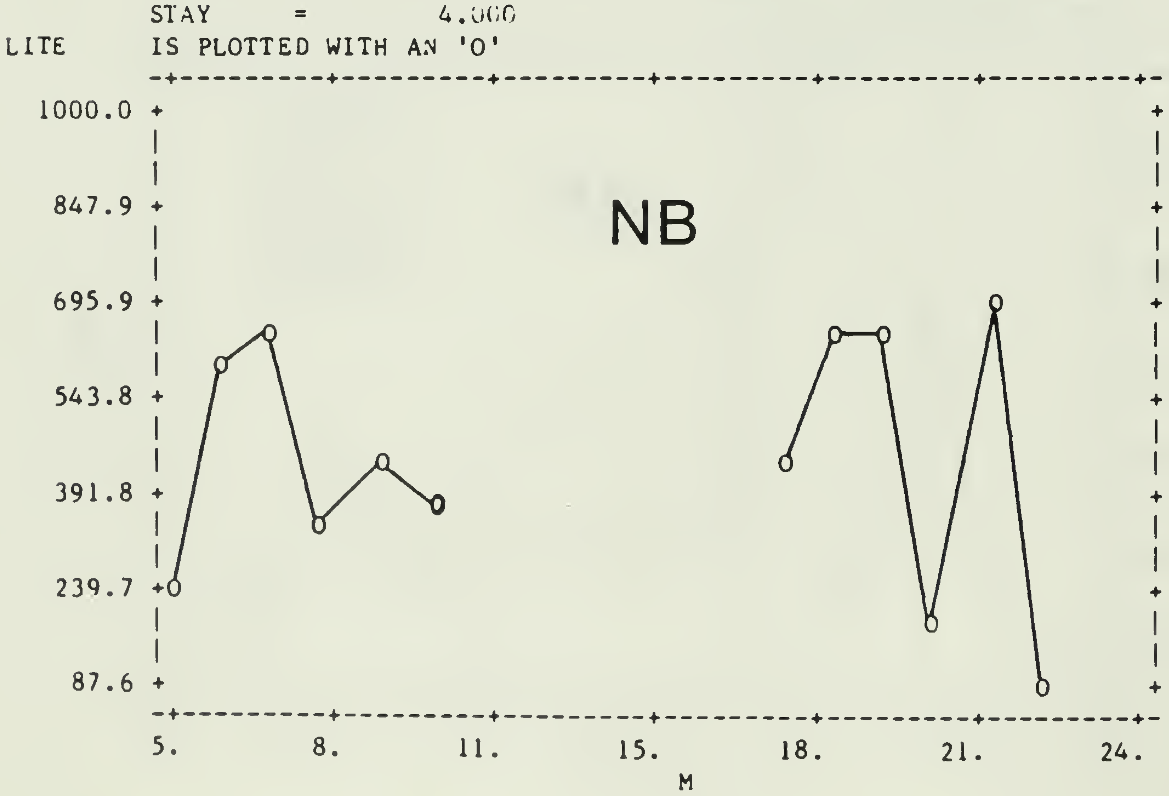
```
         STAY      =          1.000
LITE     IS PLOTTED WITH AN 'O'
```

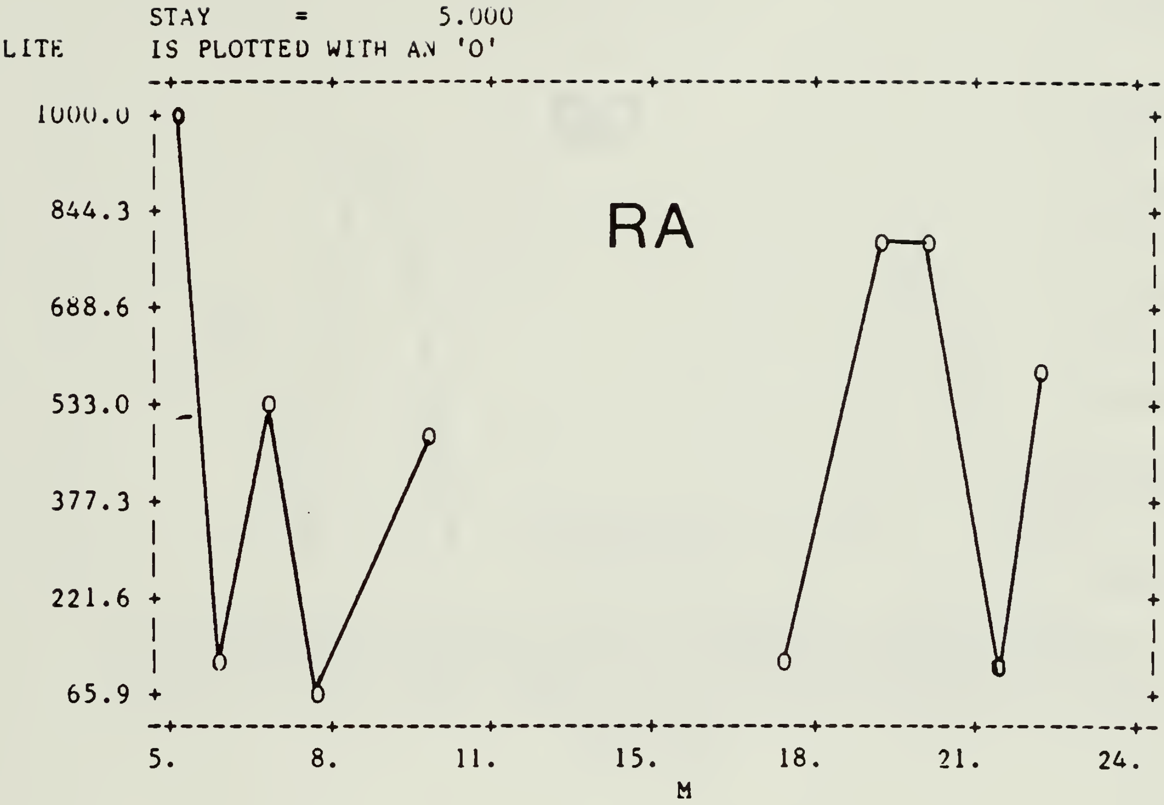


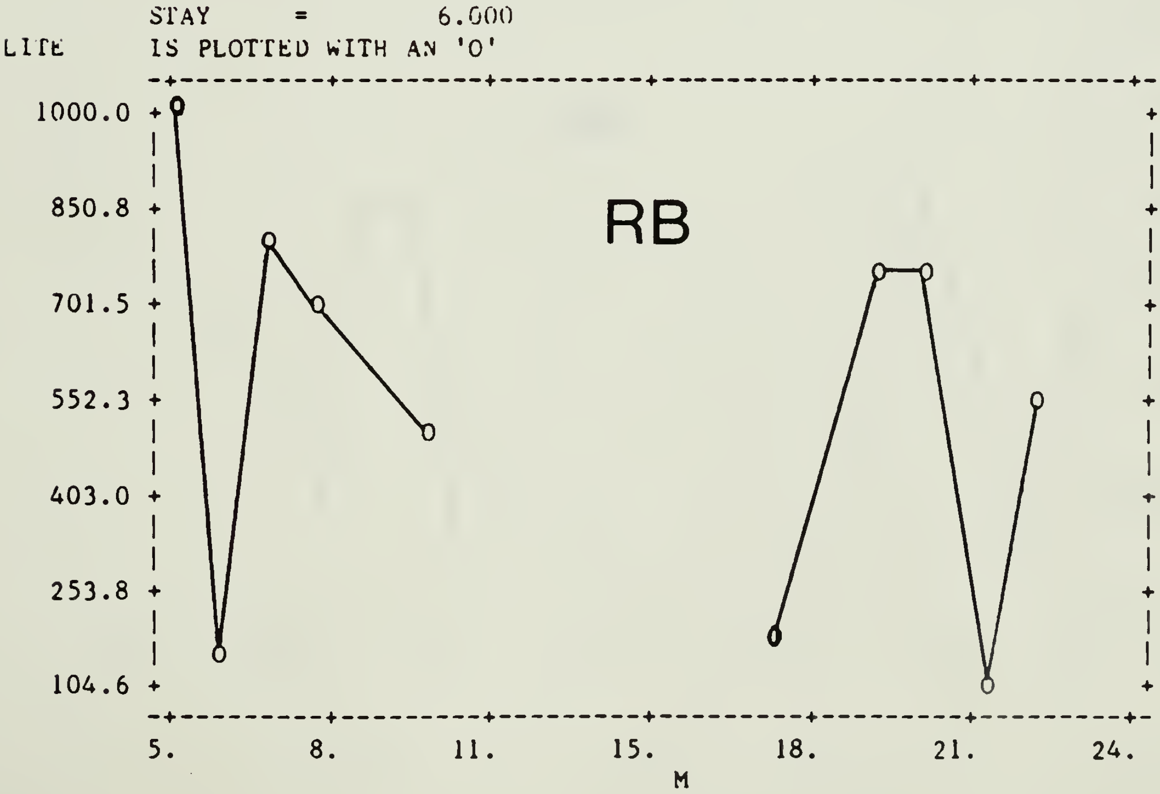
```
         STAY      =          2.000
LITE     IS PLOTTED WITH AN 'O'
```

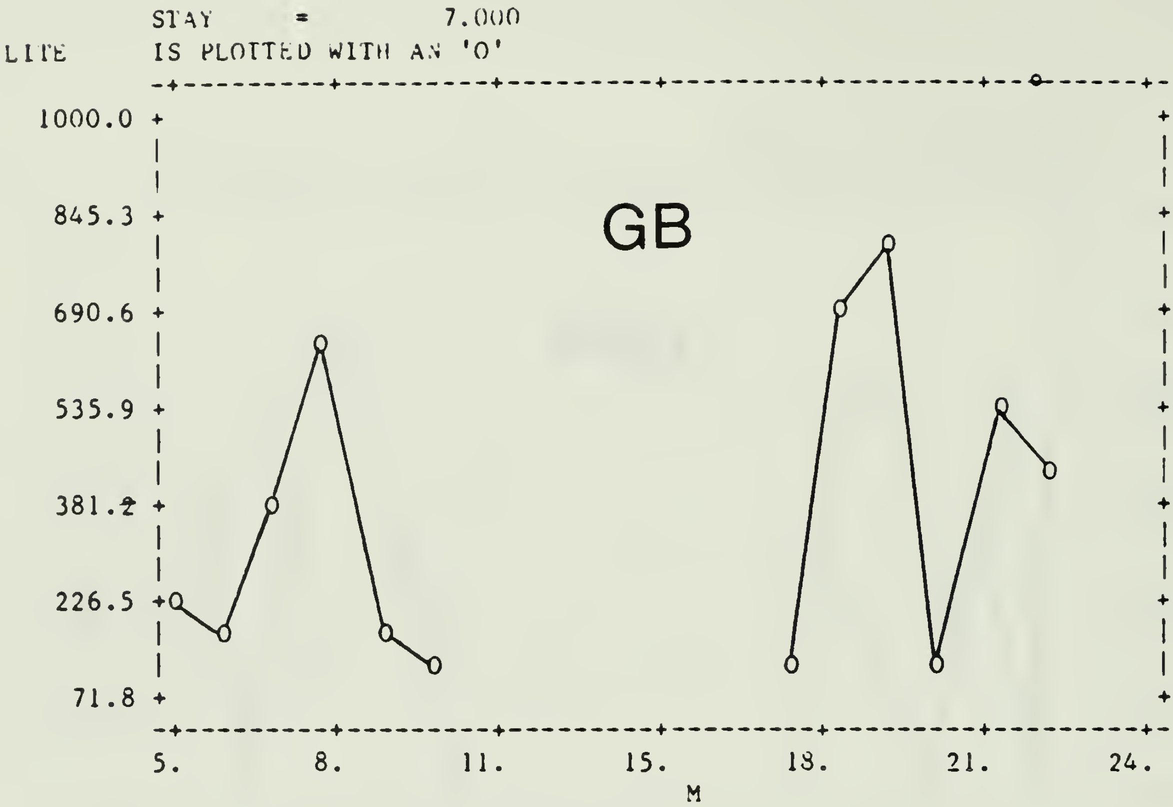


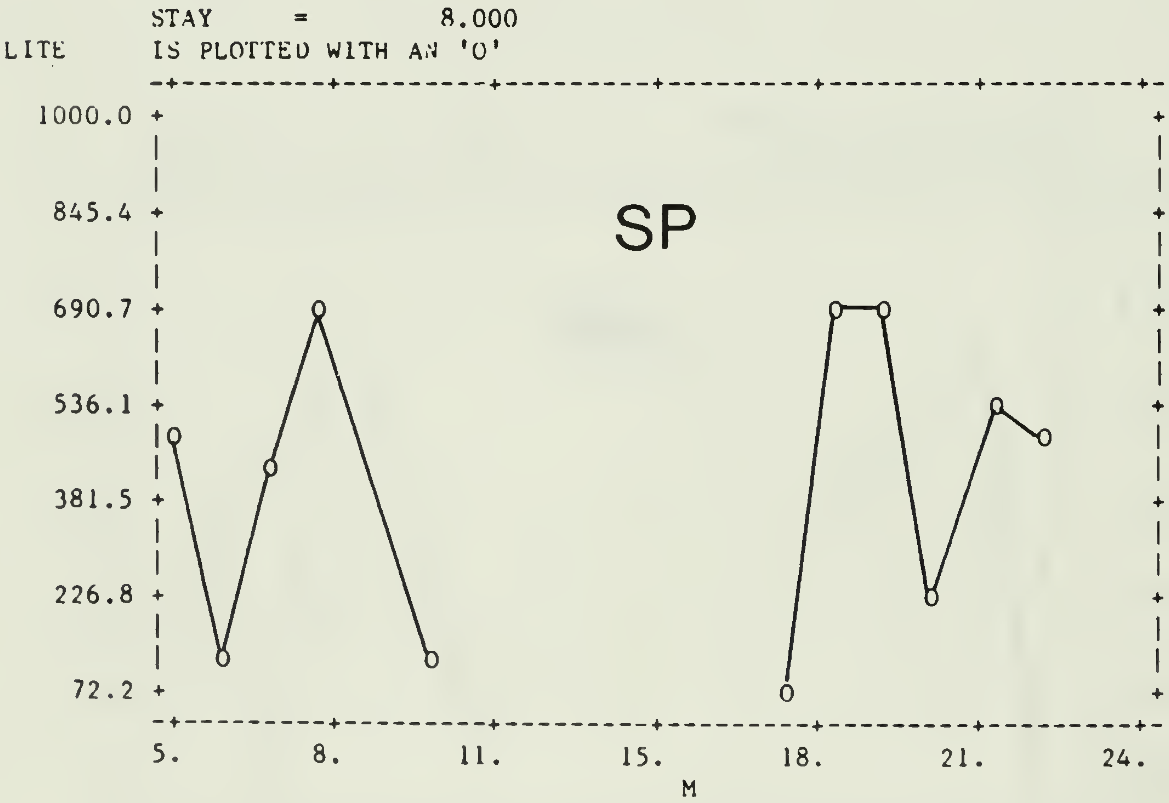

STAY = 3.000
LITE IS PLOTTED WITH AN 'O'
1000.0
850.6
701.1
551.7
402.2
252.8
103.3
NA
5.
8.
11.
15.
18.
21.
24.
M


STAY = 4.000
LITE IS PLOTTED WITH AN 'O'
1000.0
847.9
695.9
543.8
391.8
239.7
87.6
NB
5.
8.
11.
15.
18.
21.
24.
M


STAY = 5.000
LITE
IS PLOTTED WITH AN 'O'
1000.0
844.3
688.6
533.0
377.3
221.6
65.9
RA
5.
8.
11.
15.
18.
21.
24.
M


STAY = 6.000
LITE
IS PLOTTED WITH AN 'O'
1000.0
850.8
701.5
552.3
403.0
253.8
104.6
RB
5.
8.
11.
15.
18.
21.
24.
M

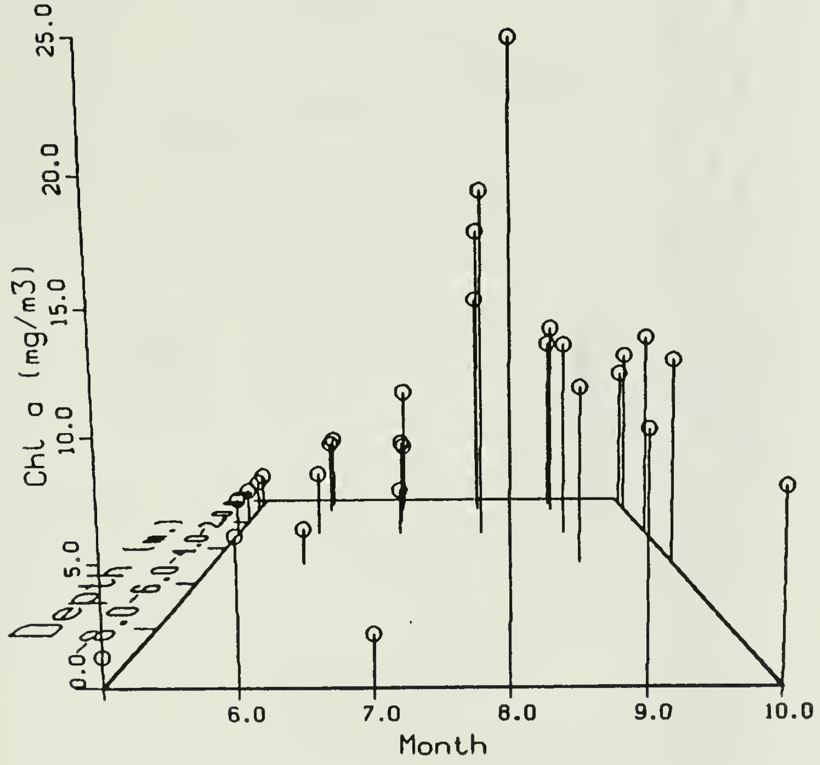

STAY = 7.000
LITE
IS PLOTTED WITH AN 'O'
GB
1000.0
845.3
690.6
535.9
381.2
226.5
71.8
5.
8.
11.
15.
18.
21.
24.
M


STAY = 8.000
LITE
IS PLOTTED WITH AN 'O'
SP
1000.0
845.4
690.7
536.1
381.5
226.8
72.2
5.
8.
11.
15.
18.
21.
24.
M

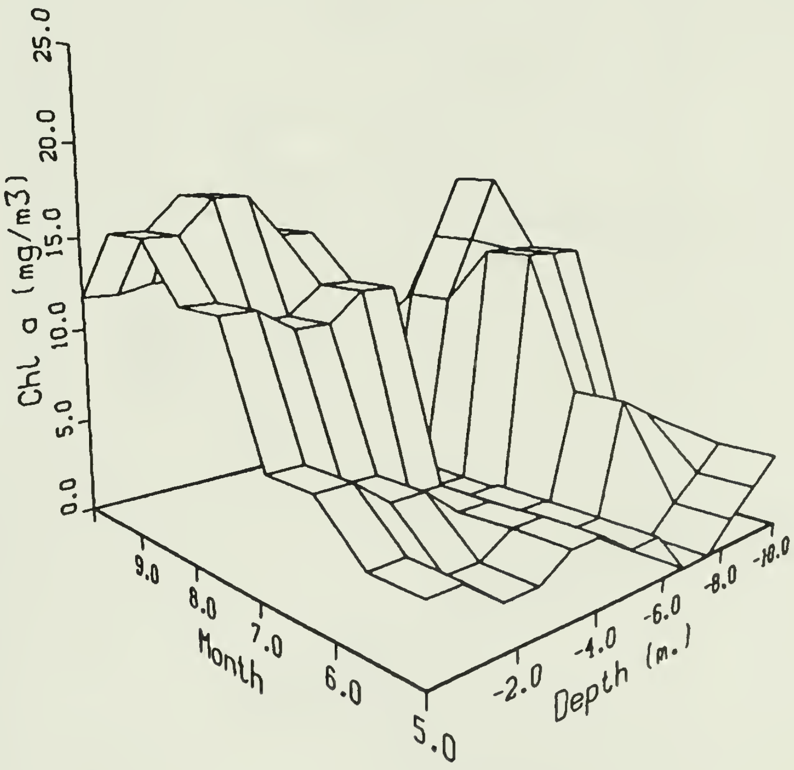
Appendix E(1)

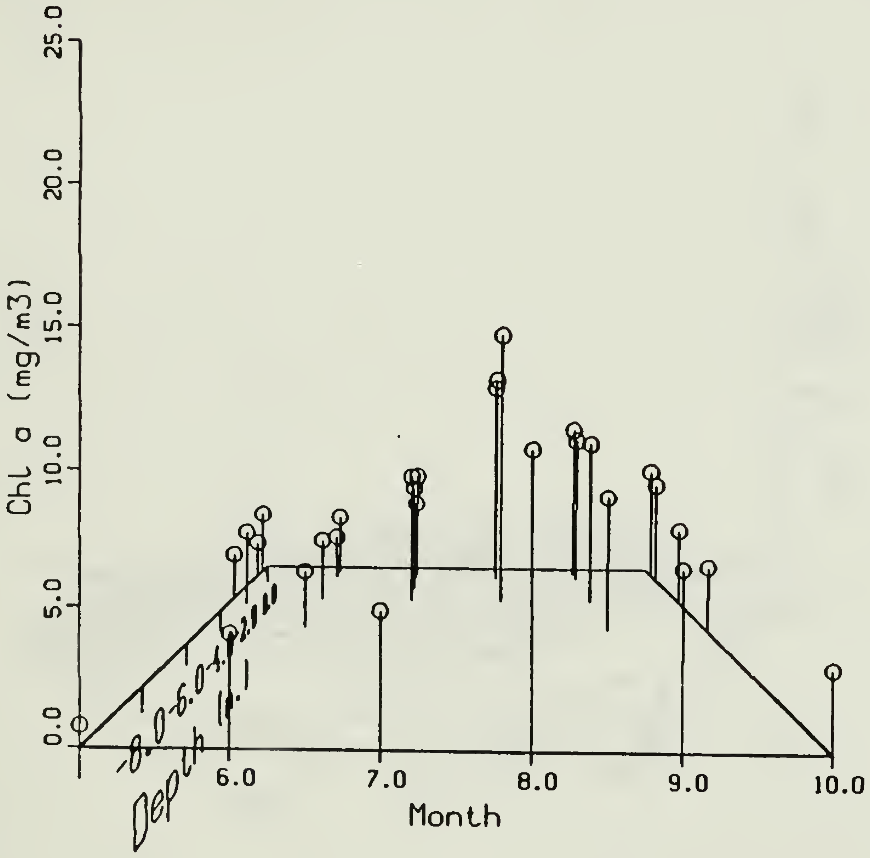
Three-dimensional "balloon" and surface plots of chlorophyll-*a* concentrations (mg m^{-3}) over depth (m) and time (months) for the eight main lake sampling stations during 1985, Voyageurs National Park, MN.

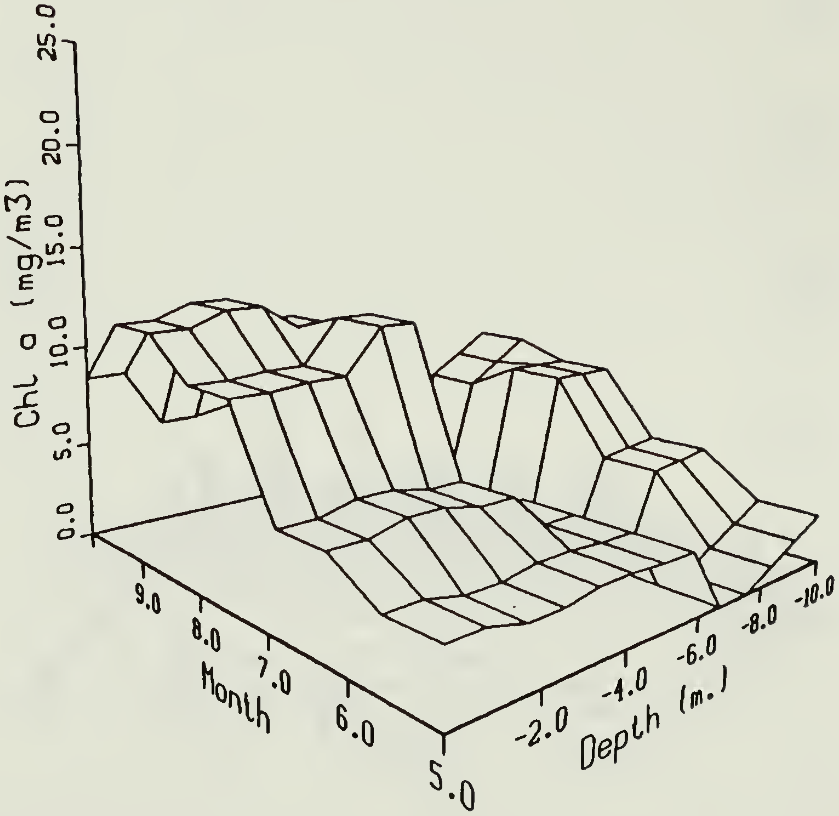
Station KA (May-Oct.)



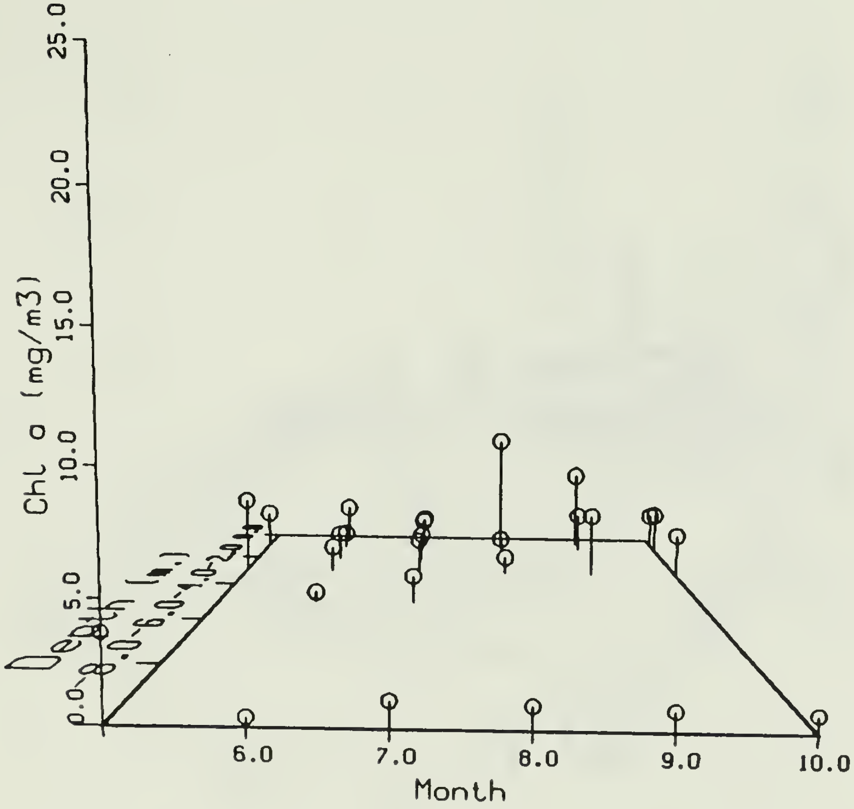
Station KA (May-Oct.)



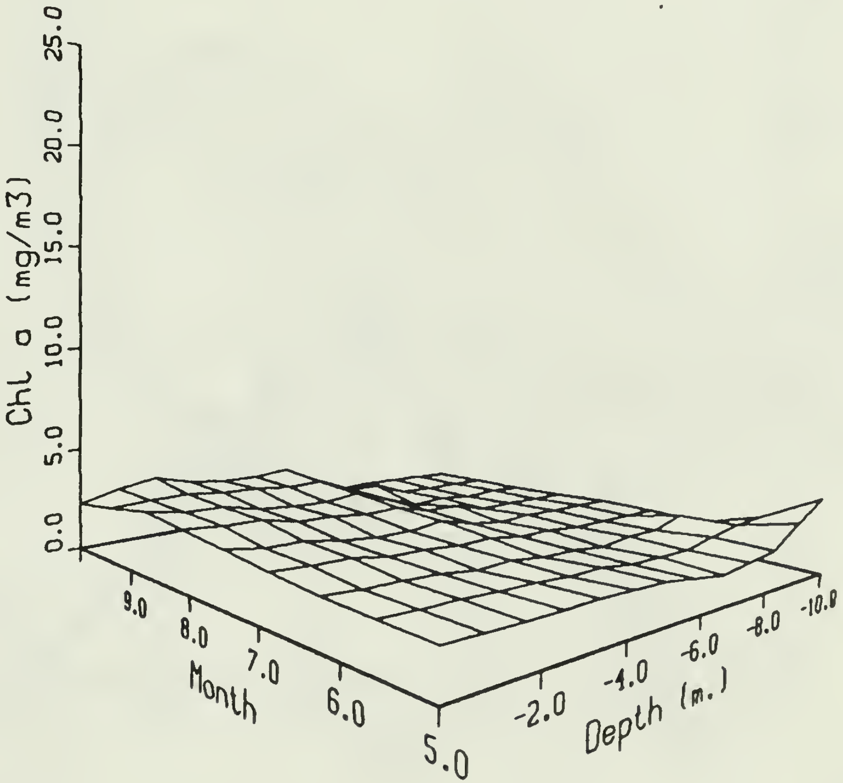

Station KB (May-Oct.)


Station KB (May-Oct.)

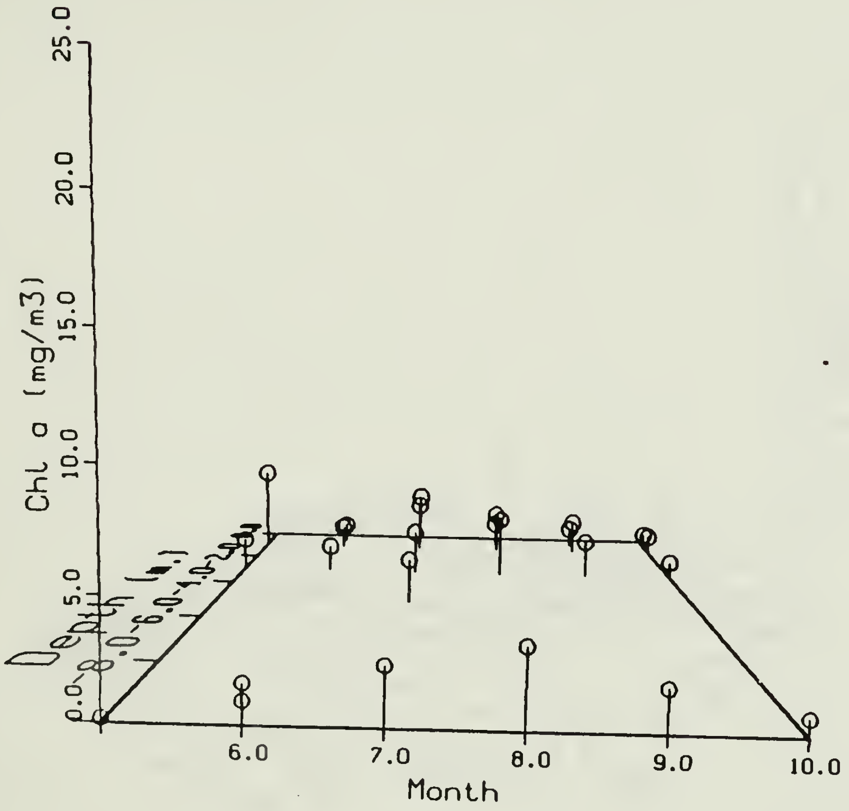
Station NA (May-Oct.)



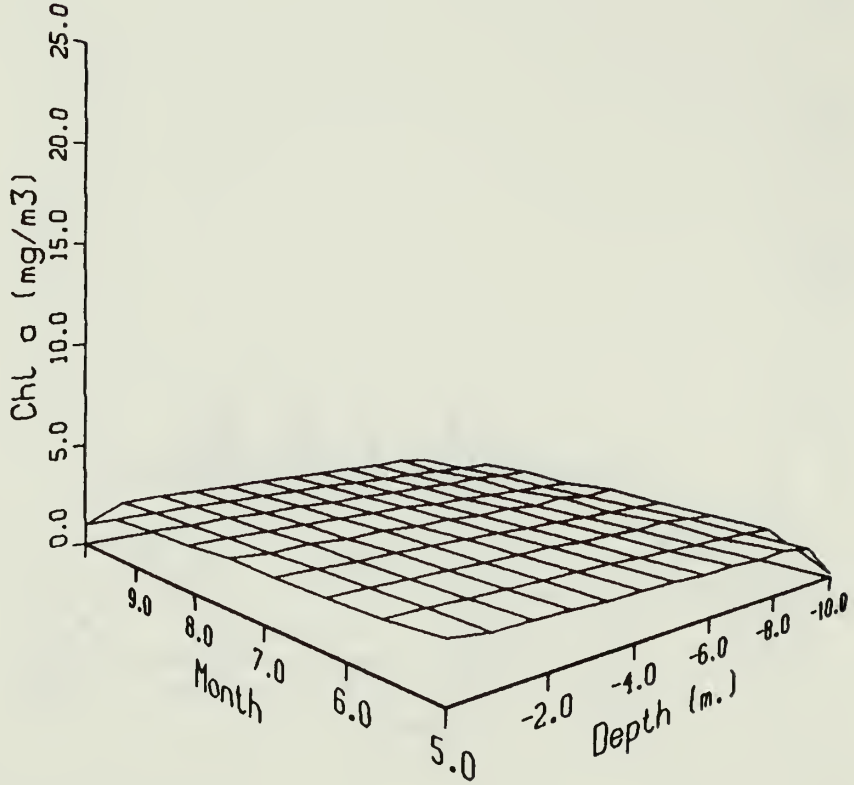
Station NA (May-Oct.)



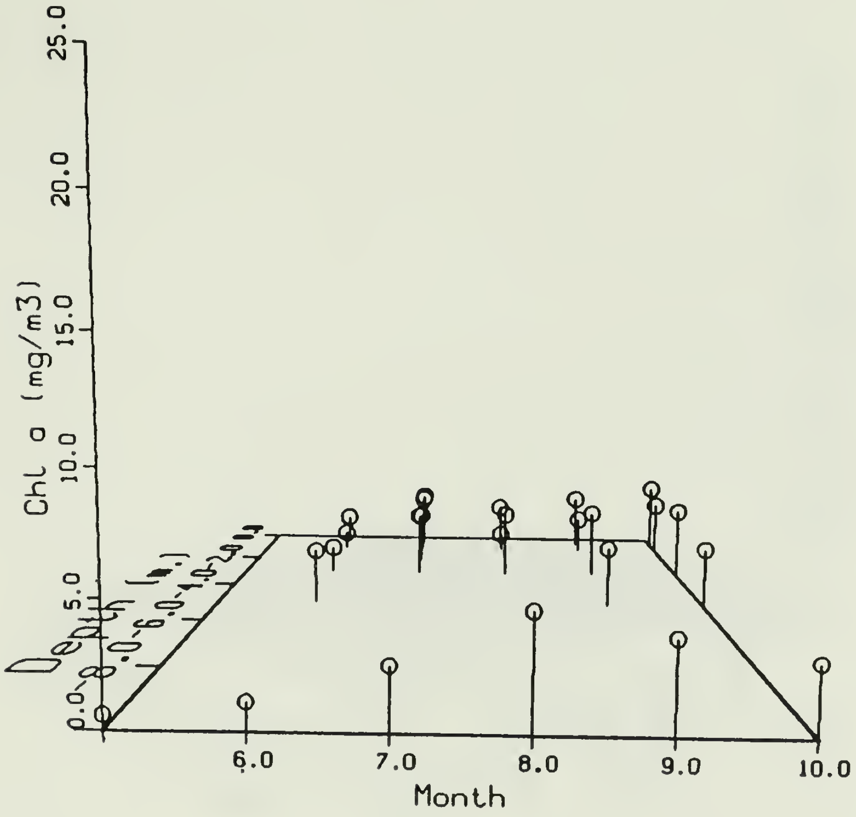
Station NB (May-Oct.)



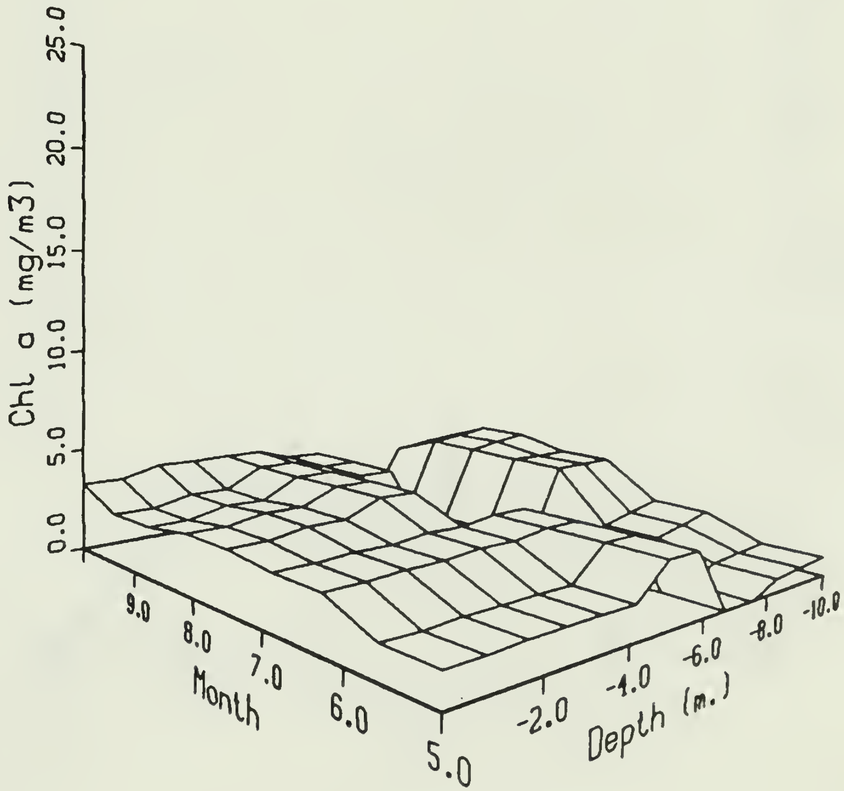
Station NB (May-Oct.)



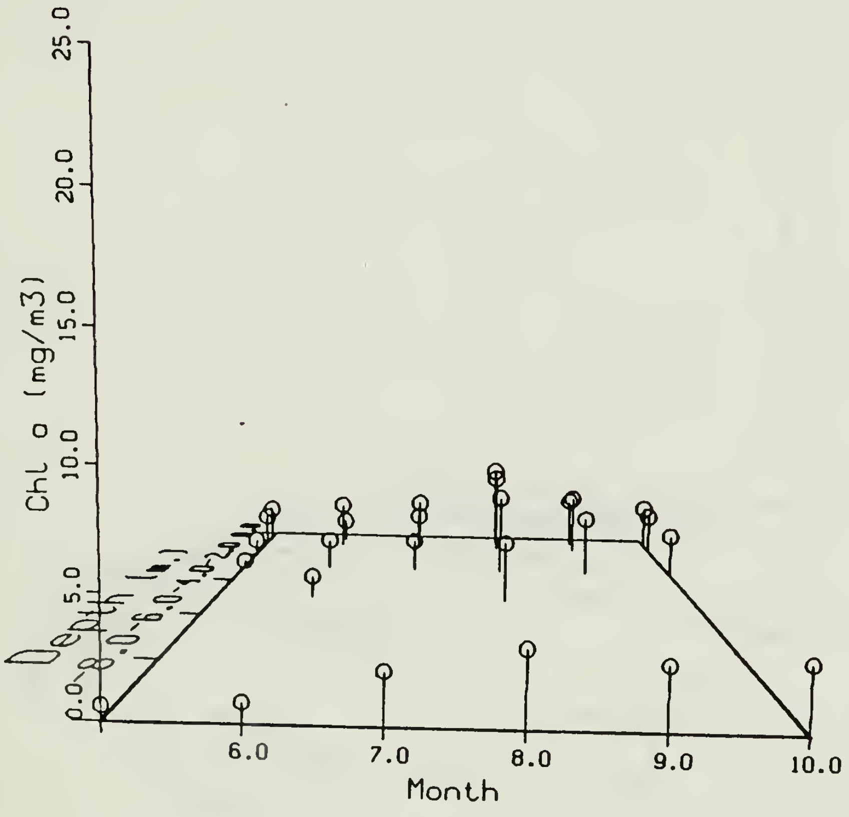
Station RA (May-Oct.)



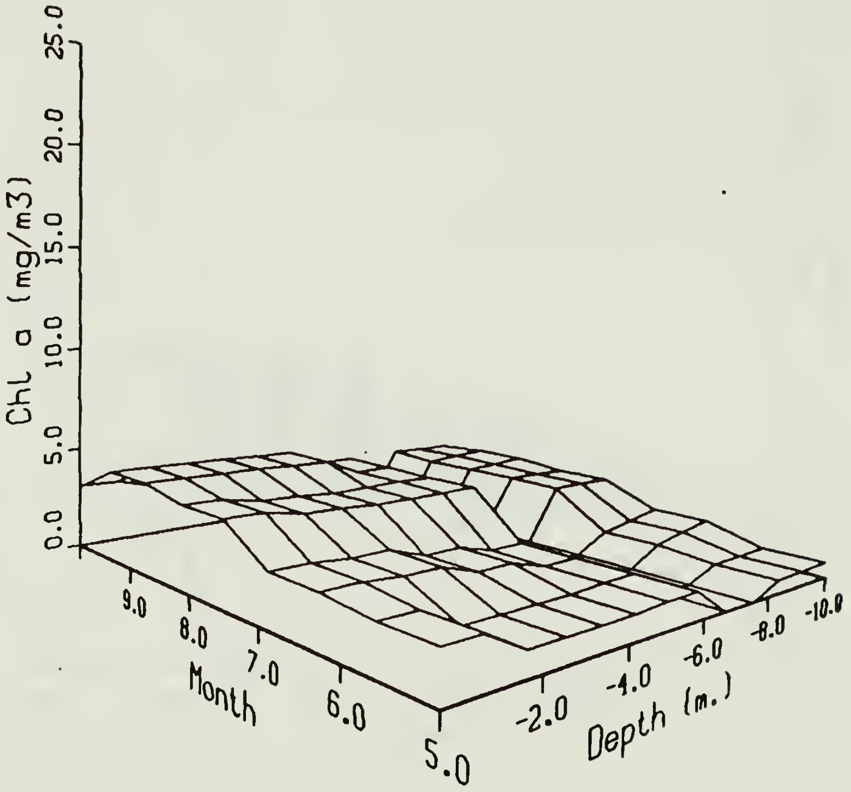
Station RA (May-Oct.)



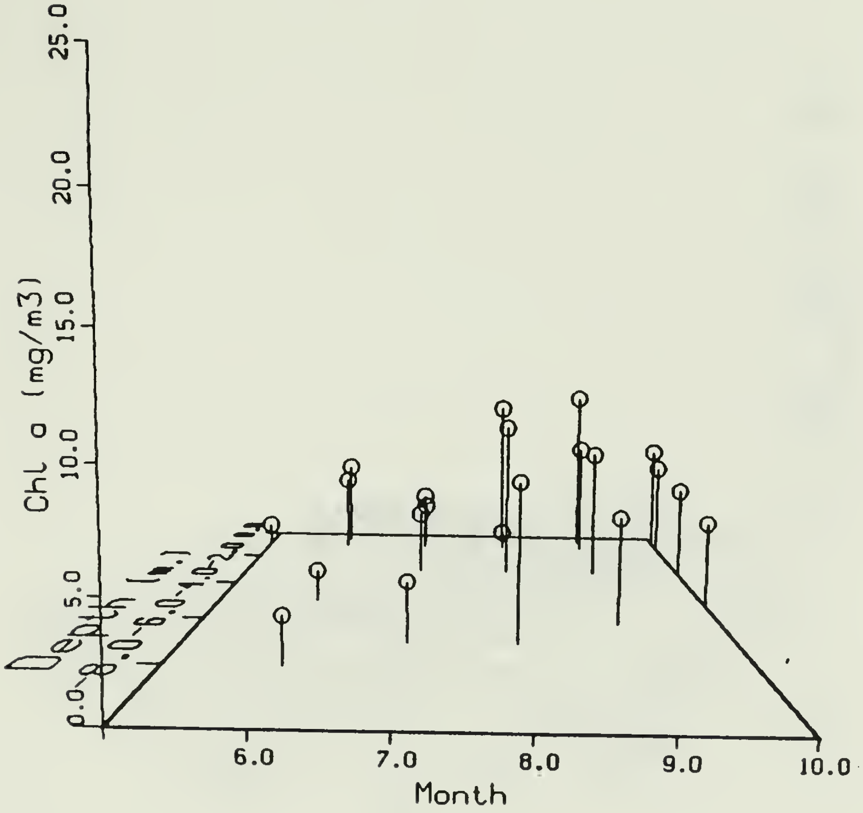
Station RB (May-Oct.)



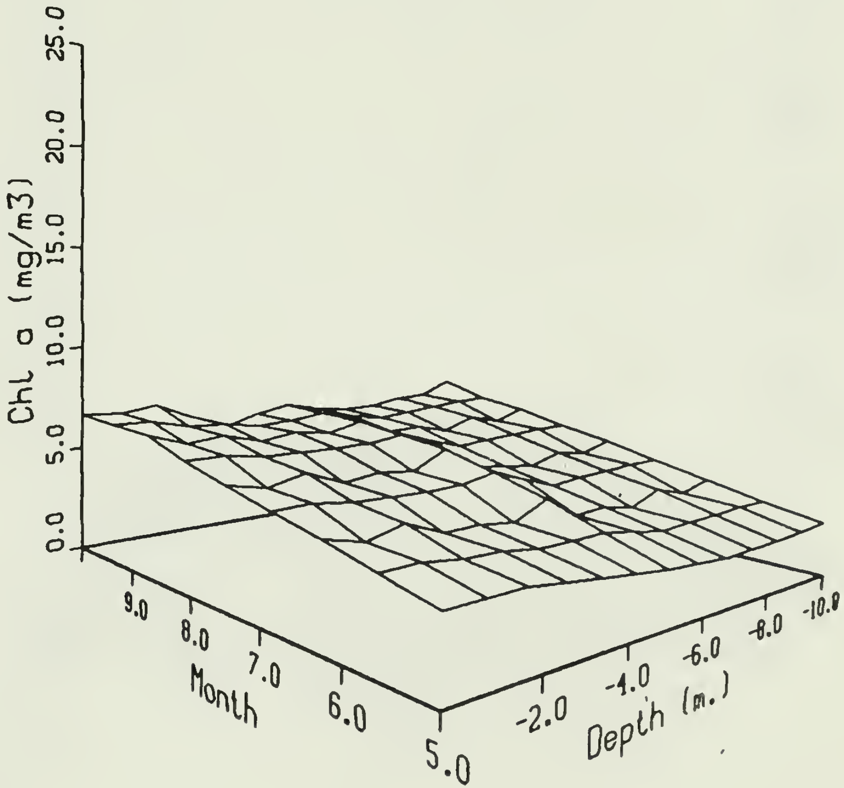
Station RB (May-Oct.)



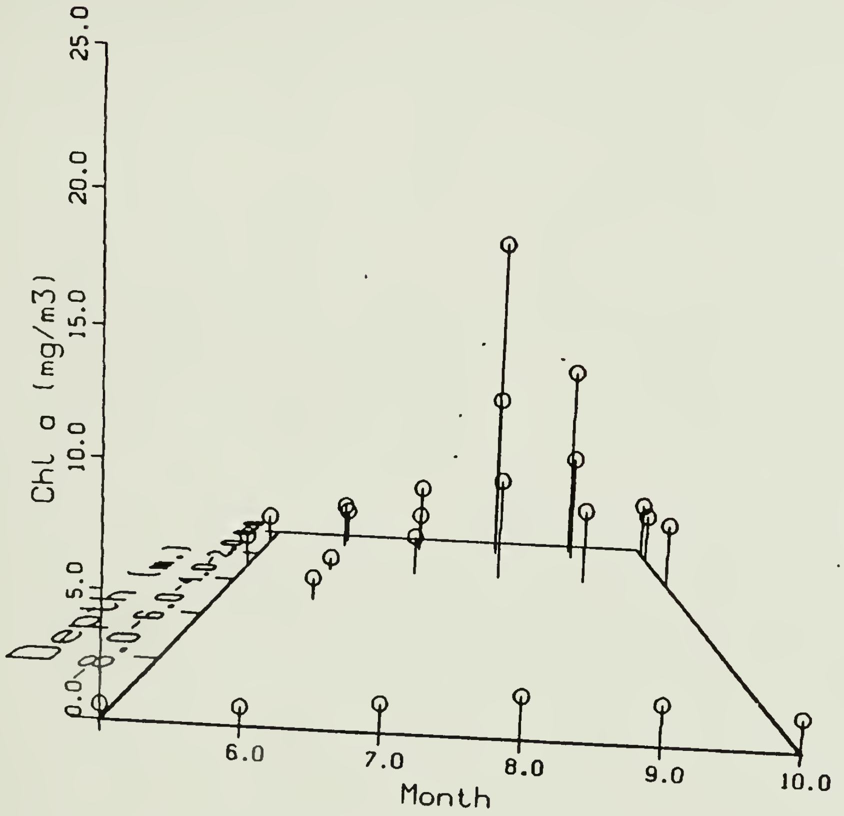
Station GB (May-Oct.)



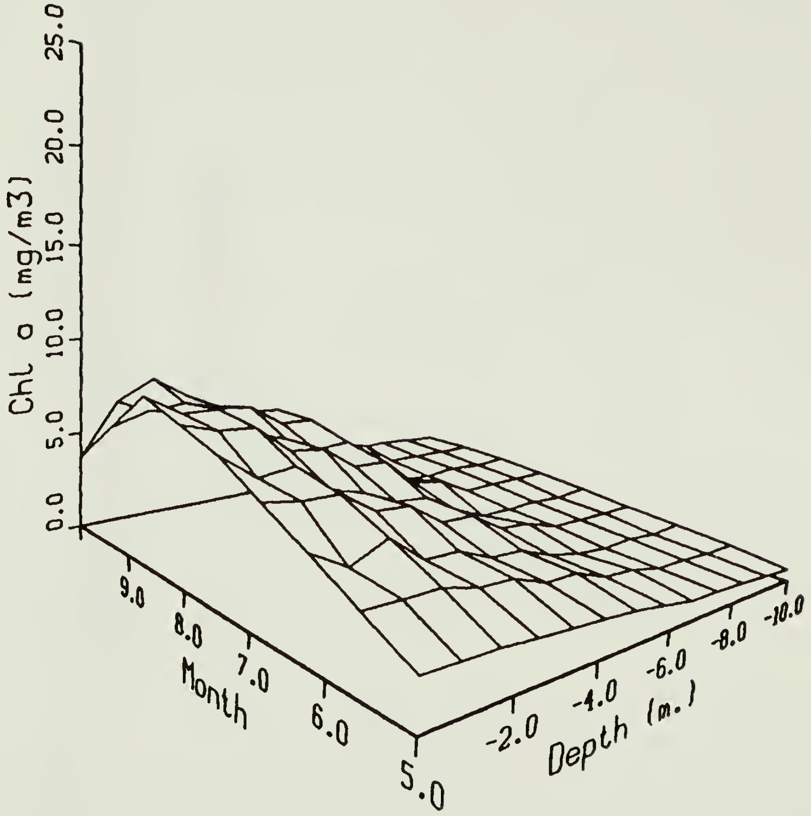
Station GB (May-Oct.)



Station SP (May-Oct.)



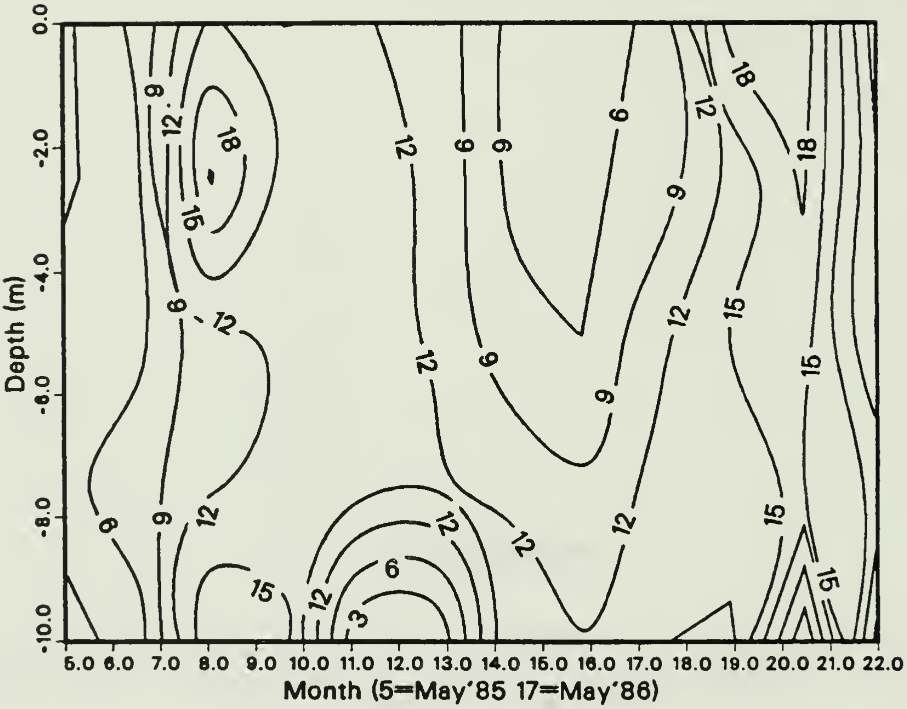
Station SP (May-Oct.)



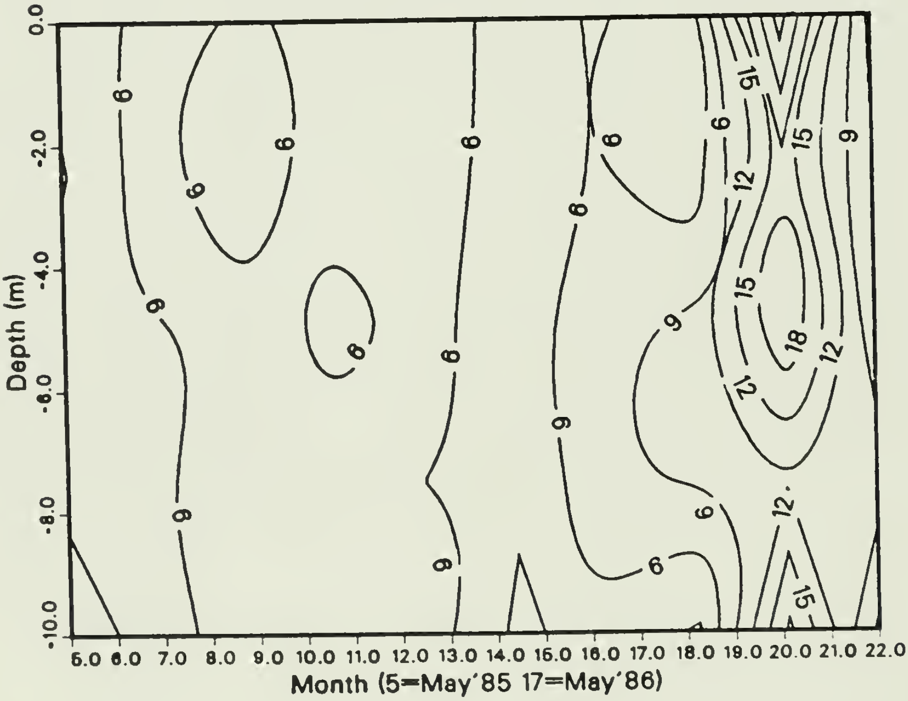
Appendix E(2)

Depth-time distribution of chlorophyll-a concentrations (mg m^{-3}) for the eight main lake sampling stations, May 1985 thru October 1986, Voyageurs National Park, MN.

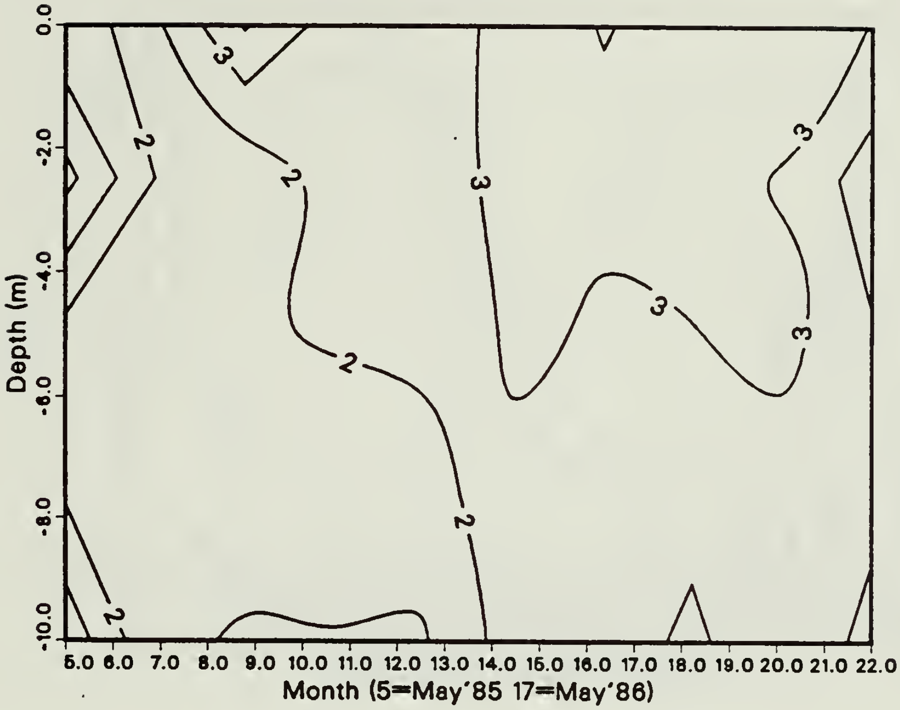
KA: Chlorophyll-a (mg/m3) over Depth and Time



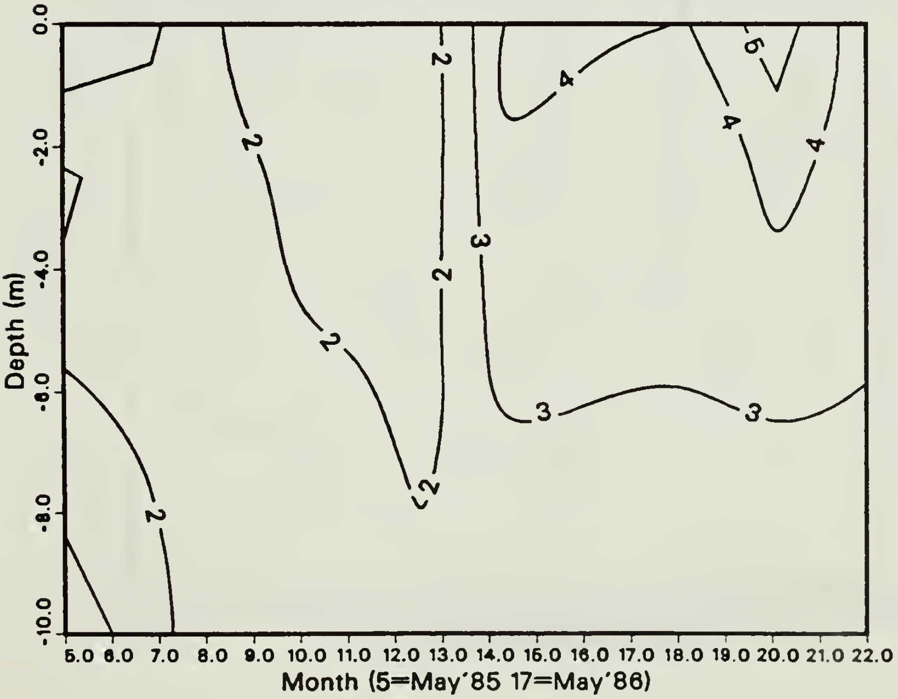
KB: Chlorophyll-a (mg/m3) over Depth and Time

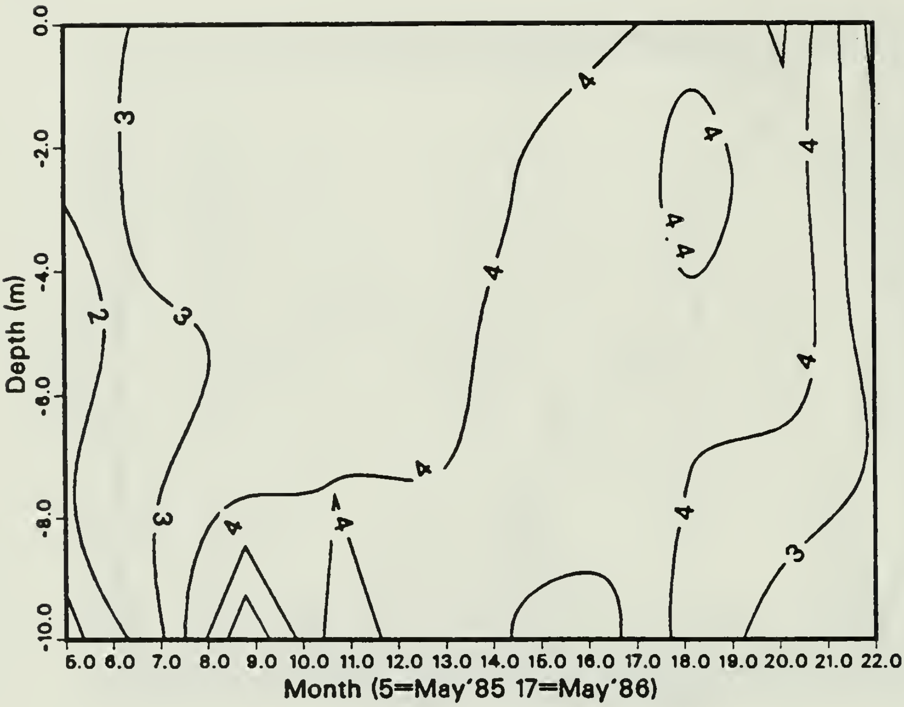


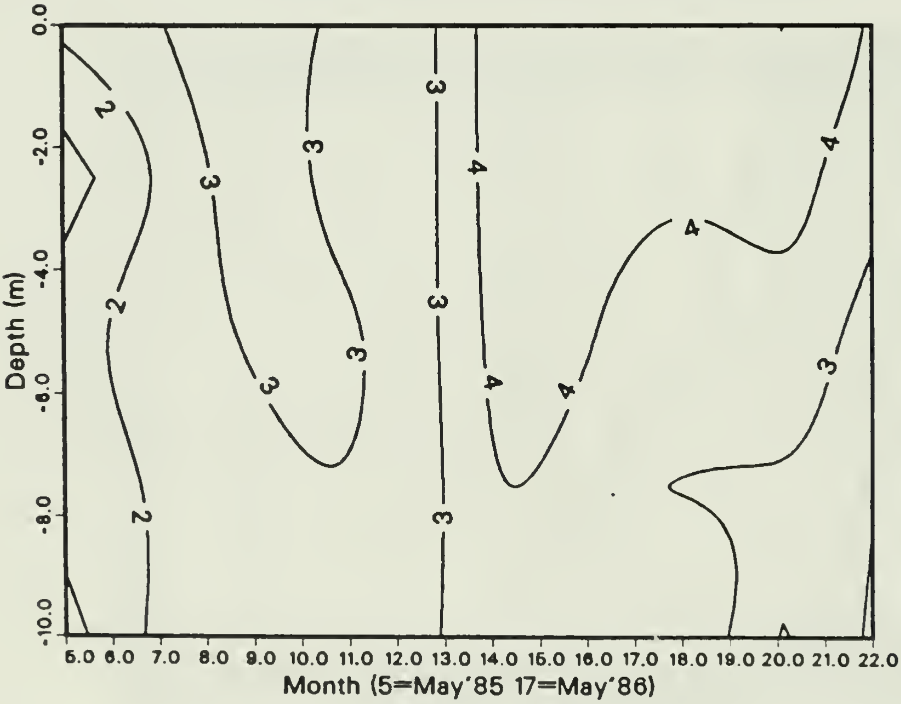
NA: Chlorophyll-a (mg/m3) over Depth and Time



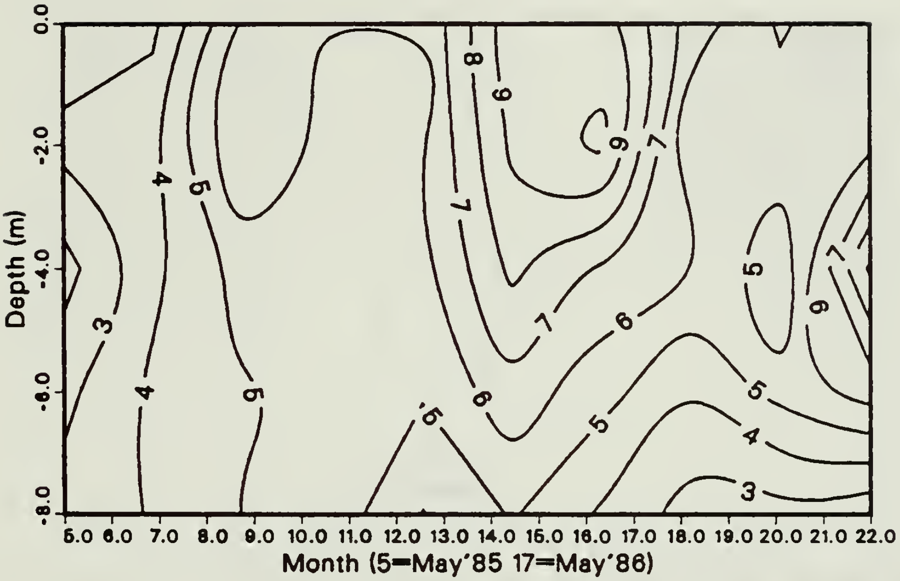
NB: Chlorophyll-a (mg/m3) over Depth and Time



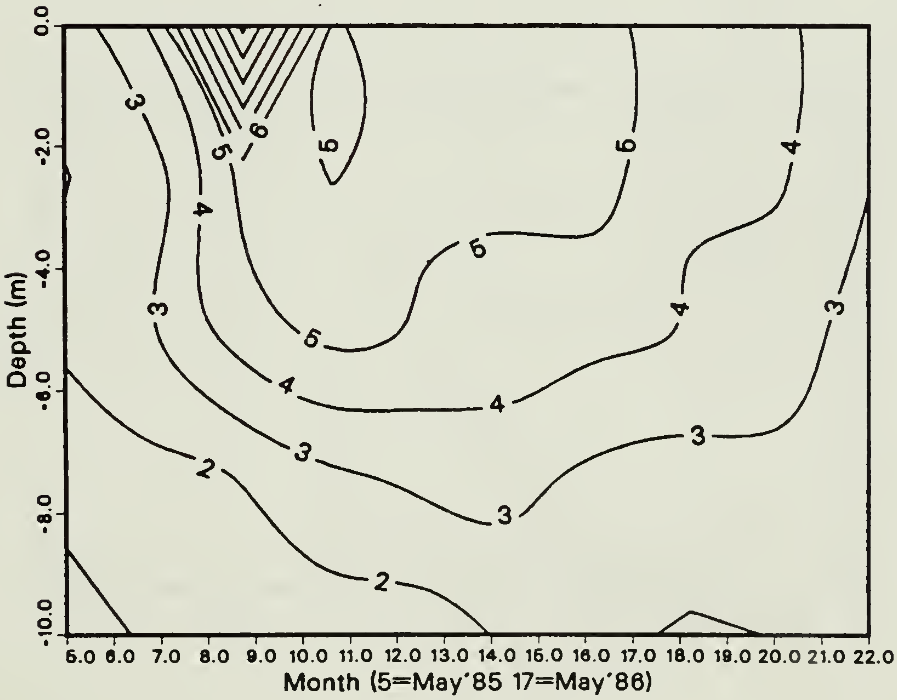

RA: Chlorophyll-a (mg/m3) over Depth and Time


RB: Chlorophyll-a (mg/m3) over Depth and Time

GB: Chlorophyll-a (mg/m3) over Depth and Time



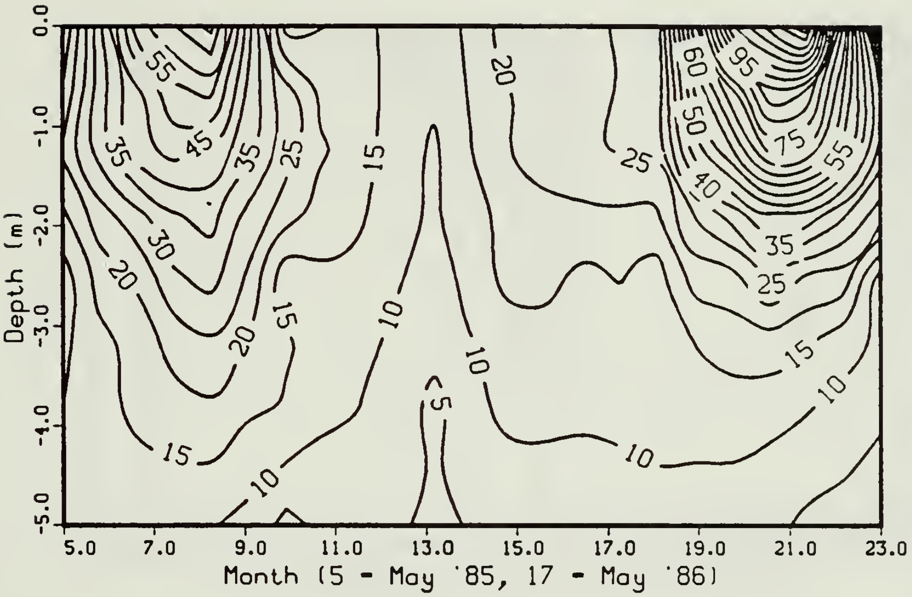
SP: Chlorophyll-a (mg/m3) over Depth and Time



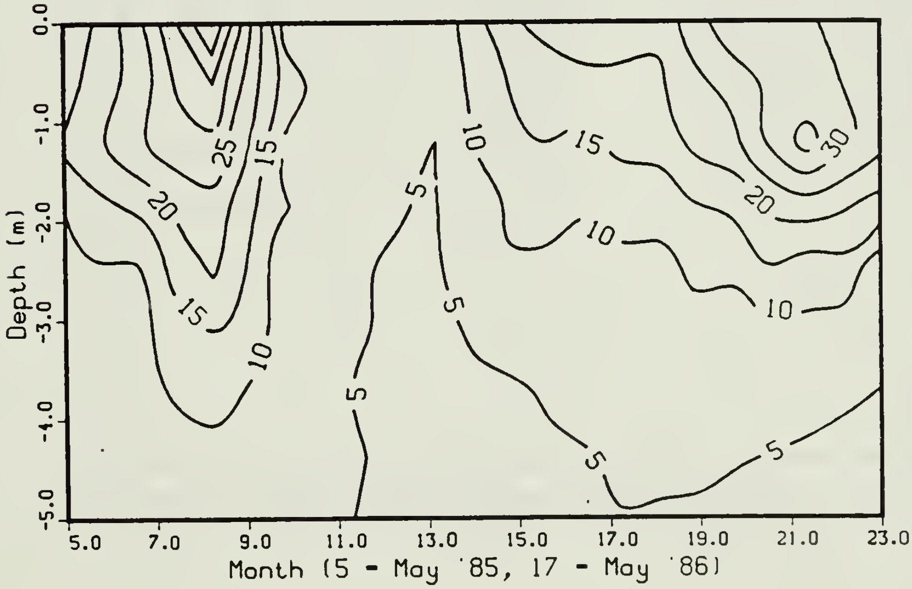
Appendix F

Depth-time distributions of *in situ* volumetric production rates (mgC m^{-3} $4hrs^{-1}$) for the eight main lake sampling stations, May 1985 thru October 1986, Voyageurs National Park, MN.

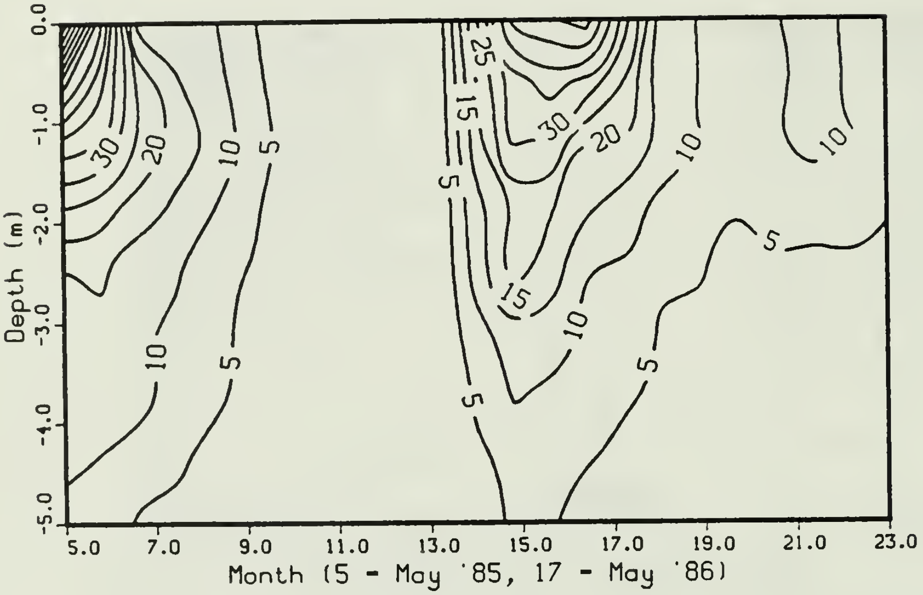
KA: C-Assimilation rates over Depth and Time



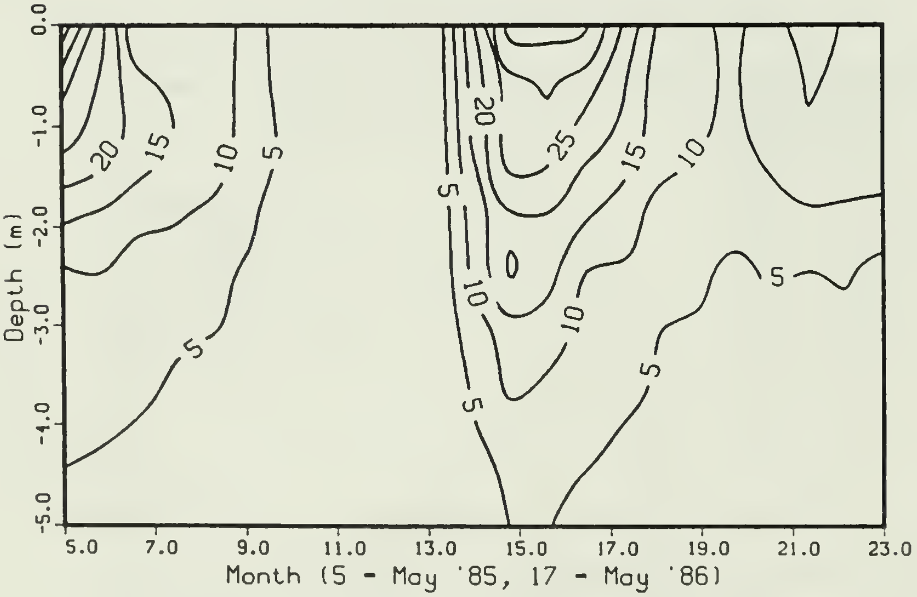
KB: C-Assimilation rates over Depth and Time

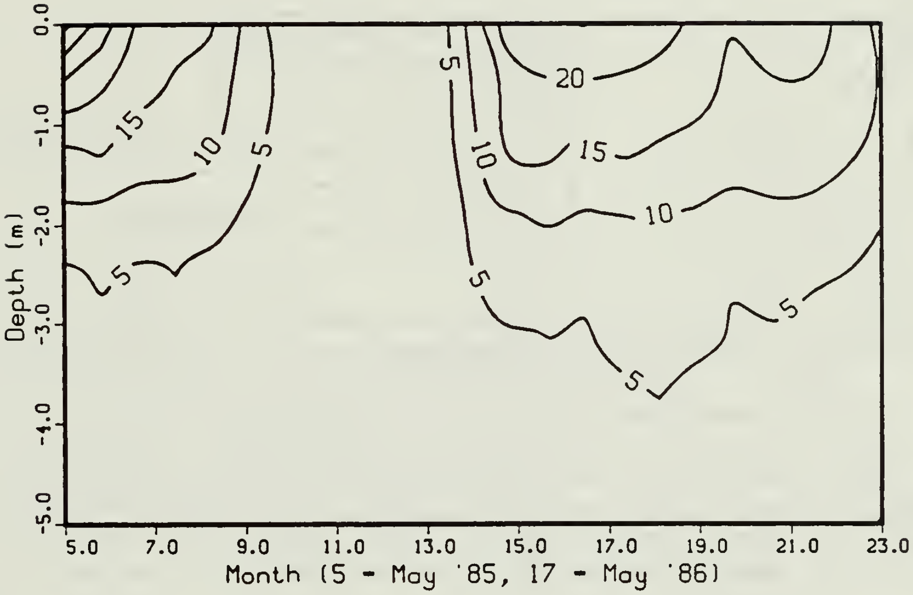


NA: C-Assimilation rates over Depth and Time

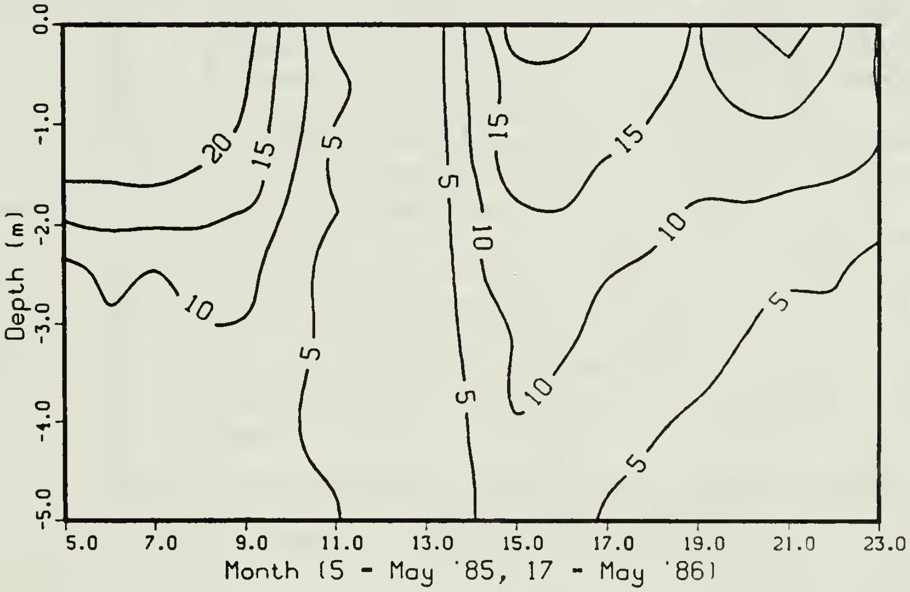


NB: C-Assimilation rates over Depth and Time

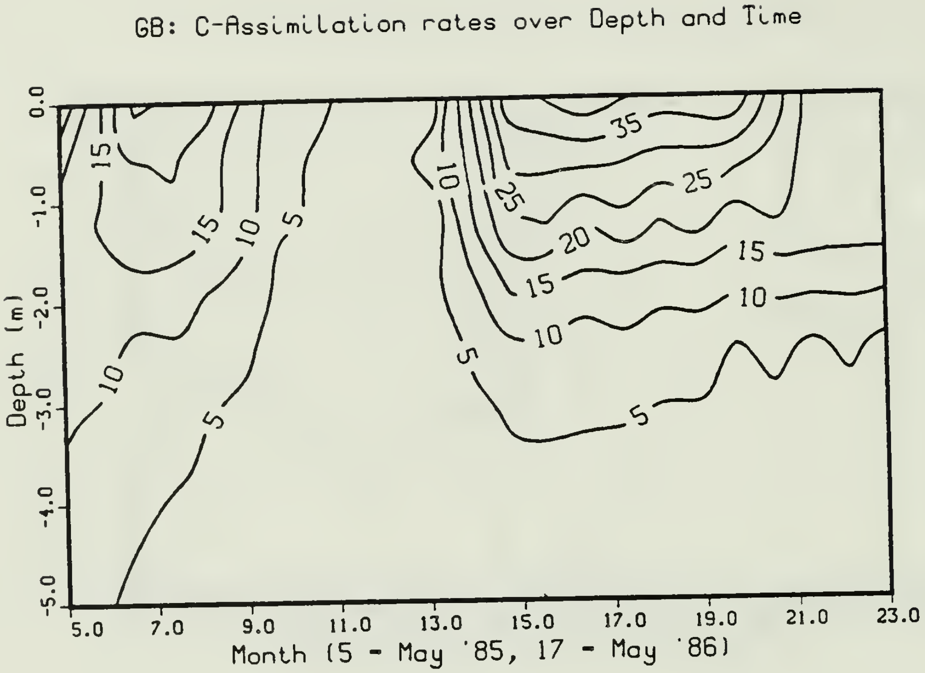




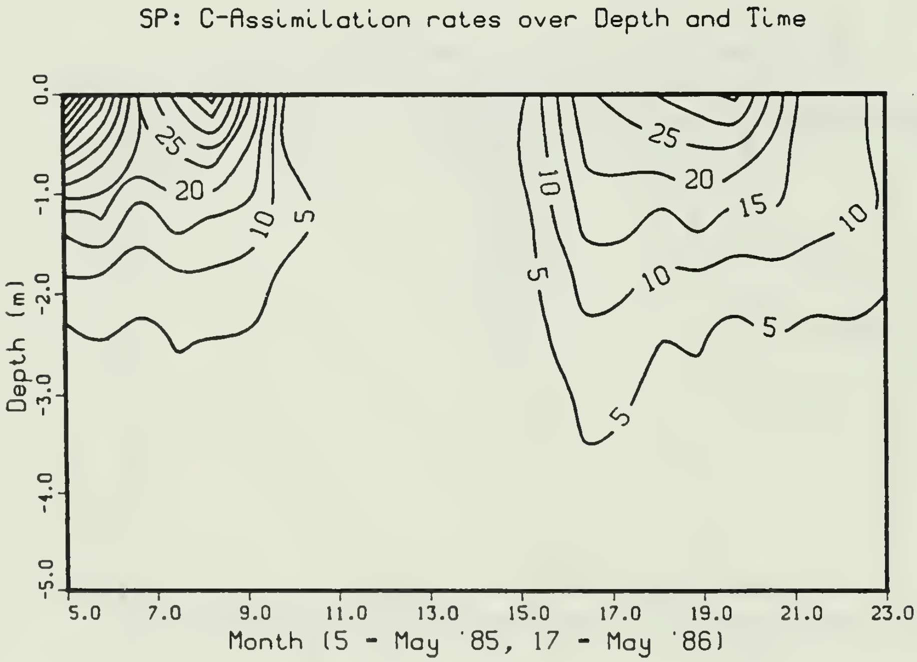
RA: C-Assimilation rates over Depth and Time



RB: C-Assimilation rates over Depth and Time



GB: C-Assimilation rates over Depth and Time



SP: C-Assimilation rates over Depth and Time

APPENDIX G

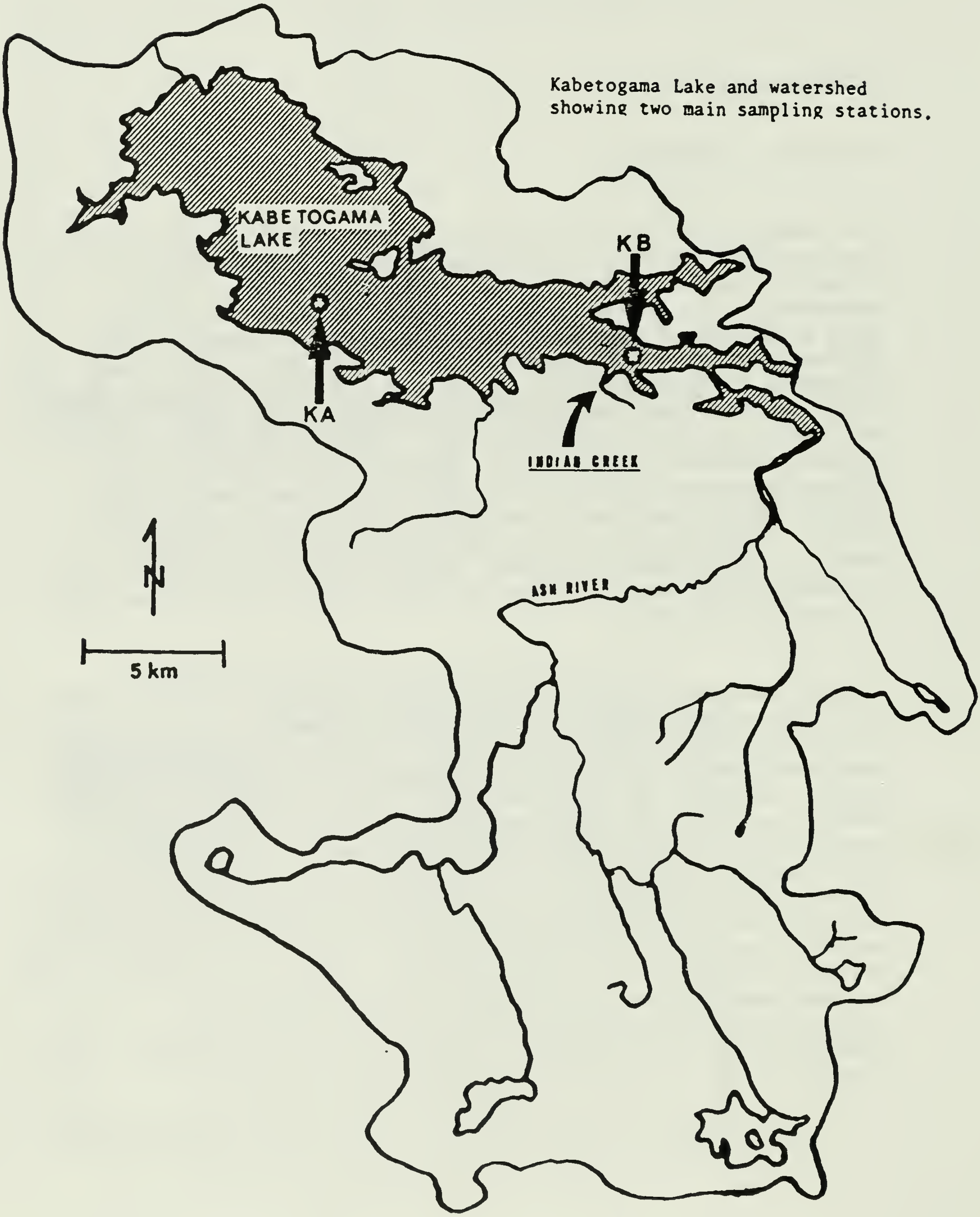
Modeling Exercise

Objective- Hypothesis:

The input of phosphorus (P) into lakes is usually cited as the most critical nutrient factor regulating algal growth in north-temperate lakes (Schindler 1971, 1977, Fogg 1973). Total-phosphorus (TP) concentration in waters has been found to be a good predictor of phytoplankton standing crop (Sakamoto 1966, Dillon and Rigler 1974, Nicholls and Dillon 1978, Oglesby and Schaffner 1978, Smith 1982, Prepas and Trew 1983, Riley and Prepas 1985, Stockner and Shortreed 1985, Pridmore et al. 1985, Premo et al. 1985, Ostrofsky and Rigler 1987). Despite the lack of actual TP data obtained in this study, phosphorus was chosen as the modeled component because it is most rapidly and commonly the first limiting nutrient in the majority of lake systems (Wetzel 1975). Kabetogama Lake (Fig. 38) was chosen as the system to model, as it is apparently most influenced by the drawdown. This is particularly true in terms of percent total volume reductions accompanying drawdown.

Testing Kabetogama Lake as a completely-mixed flow reactor (CMF), a TP mass-balance model has been used to examine dilution/concentration effects due to volume variations in this regulated lake. It must be noted that this is only a preliminary model. Although the input parameters are approximations and the model remains uncalibrated and unconfirmed, the simulation provides one test of whether Kabetogama Lake's comparatively unique trophic status may be attributed to the direct effects of drawdown on a potentially limiting nutrient concentration. On a differential time and volume basis, model parameters include basin runoff, atmospheric and septic loadings, while sinks include suspension outflow and settling losses. The main objective is to compare model-generated seasonal total-phosphorus (TP) concentrations under current (1986) drawdown conditions with those generated under non-drawdown (constant volume) or computed "natural" (ie., undammed) mean lake level conditions.

Figure 38. Kabetogama Lake and watershed with major tributaries, showing two main sampling stations and the Indian Creek stream monitoring site.


Kabetogama Lake and watershed showing two main sampling stations.
KABETOGAMA LAKE
KB
KA
INDIAN CREEK
N
5 km
ASH RIVER

Model Explanation:

All model TP loadings are time-variable. Constant parameters include lake and drainage basin areas and TP settling velocity. Basin flow and volume fluctuations are empirical relationships taken from streamflow and lake elevation data collected during 1986 (Lake of the Woods Control Board 1986). This flow and volume data was fitted with a quadratic equation over a one year (1986) period. The differential volume equation was taken as the first derivative of the volume quadratic, and is computed in the same manner as flow and volume.

The phosphorus budget equation is in the form of:

$$dC/dT = W/V - (C/V) * [Q + dV/dT + (V*k)]$$

Where: W = Total-P loading (μg day^{-1})

V = Lake volume (L)

C = Total-P concentration in lake (μg L^{-1})

Q = Outflow from system (L sec^{-1})

k = Settling velocity (day^{-1})

dV/dT = Differential volume (L day^{-1})

dC/dT = Differential concentration (μg L^{-1} day^{-1})

This equation (after Canale 1976) is then solved using the Euler integration technique for rate equations.

Variables and Sources:

Septic loadings are based on a time-variable population within the Kabetogama drainage (Larry Keck, Chairman Kabetogama Lake Association, pers. comm.). Population is multiplied by a figure of 2.25 gP caput^{-1} day^{-1} (Vollenweider 1968) to yield the time-variable septic P-loading.

Atmospheric loadings are based upon wet-only amounts measured at NADP/NTN station #241660 at Marcell Experimental Forest and was multiplied by a mean annual precipitation concentration of 0.05 $\mu g\ L^{-1}$ (IJC 1976) to yield the time-variable atmospheric P-loading.

Basin unit area loads were taken from the value of 0.09 kg $ha^{-1}\ yr^{-1}$ assigned for forested Canadian Shield lands (Gregor and Johnson 1980), and normalized according to actual basin runoff volumes for 1986 collected at the Indian Creek gaging station. Runoff loadings were extrapolated to the entire Kabetogama basin based upon area, assuming that Indian Creek runoff volumes were representative of the basin in general.

Outflows and lake elevations (Kabetogama Lake at Gold Portage) were obtained from Minnesota Hydrological Data, Lake of the Woods Control Board, Rainy Lake Drainage Basin, 1985-1986.

The initial TP concentration chosen for model runs (30 $\mu g\ L^{-1}$) was back-calculated from mean chlorophyll-based TSI values (Carlson 1977) based upon Kabetogama Lake mean summer chlorophyll-a concentration (8.36 mg m^{-3}) of this and a previous study (Hargis 1981).

Settling velocity (1 m yr^{-1}) was determined by calibration so that final TP concentration at the end of a one year run would be approximately equal to initial TP concentration.

Model Assumptions:

A major assumption of the CMF model is complete mixing within the system. This implies that TP concentrations are homogeneous throughout the lake and any vertical or horizontal stratification is negligible. Kabetogama Lake is usually unstratified throughout the ice-free period although weak stratification may be established during periods of hot, calm weather (see Water Temperature). The lack of marked vertical stratification during most of the year seems a reasonable assumption. Horizontal differences within Kabetogama are evident in comparisons between stations KA and KB, yet are not accounted for in the single-cell model.

It is assumed that all TP sources and sinks are accounted for in the model, and that inflows, outflows, and lake level data are reasonable. It is therefore assumed that the removal of phosphorus from the lake system occurs through only two possible pathways, the outlet, and the sediments. Though the settling coefficient is a function of lake depth, it is assumed that settling velocity is constant throughout the year. This is probably not the case, particularly during times of ice-cover and winter stratification. It is also assumed that precipitation TP concentration is constant throughout the year, though atmospheric inputs comprise such a small fraction of total loading as to appear insignificant.

Model Results:

The model is highly sensitive to the settling velocity incorporated. Either settling losses are not effecting the system to a large extent, a much higher TP load than calculated is being introduced, or another unconsidered factor is involved. It is possible that this missing factor is re-release of phosphorus from sediments. That sediments are considered sources as well as sinks for TP remains unaccounted for in the present model. Phosphorus removal and release rates from sediments are complicated, multidimensional variables; dependent upon influent and effluent P mass, lake geomorphology and hydrology, the dissolved oxygen concentration and pH at the sediment-water interface, the concentration of major cations (Ca, Fe and Al) that combine with P and transport it or hold it in the sediments and additional mechanisms important on a limited scale (Reckhow and Chapra 1983). It is obvious that the expression of the TP loss term as it is used in this model is a gross oversimplification.

The model is also very sensitive to the differential volume of the system as expected. Little difference is found in predicted TP concentrations under variable flow versus constant flow conditions. Thus, the model seems to be more dependent upon variable volume than variable flow. A comparison of model-predicted TP concentrations under 1986's actual lake-level regime with those predicted based on a constant-volume system held at the mean annual lake volume (ie., dV/dT in the mass-balance = 0) is presented in Figure 39. Total-P concentrations are presented in model output in $\mu g\ L^{-1}$ (ppb), over a one year period. Given an initial TP concentration of 30 $\mu g\ L^{-1}$, we see that predicted TP concentrations under constant-volume conditions do not fluctuate by more than 1 or 2 $\mu g\ L^{-1}$. However, under the 1986 lake level regime, concentrations varied from roughly 33 down to 22 $\mu g\ L^{-1}$. The sharpest drop in lake levels, between November and March, coincides with the sharpest increases in predicted TP concentrations under 1986 conditions. Simulated concentration then drops as Namakan Reservoir is allowed to refill, reaching lowest concentrations at approximately the same time as peak lake level in early July.

Of course it is unrealistic to consider Kabetogama Lake in terms of a constant-volume system. Therefore, in the second model run presented (Fig. 40), predicted TP concentrations are based upon "natural" (ie., undammed) conditions. The differential-volume equation used for this run is based upon projected undammed mean lake levels as computed by the U.S. Army Corp of Engineers as part of their assignment for the Rainy Lake Control Board (Flug 1986). Although mean annual predicted TP concentrations are no lower under projected "natural" conditions than under actual 1986 conditions, concentration fluctuations are attenuated. Also, given the same initial concentration at time zero (30 $\mu g\ L^{-1}$) and a one week step size, final concentration after 365 days is slightly lower (27.13 $\mu g\ L^{-1}$) under "natural" conditions than under 1986 conditions (27.92 $\mu g\ L^{-1}$).

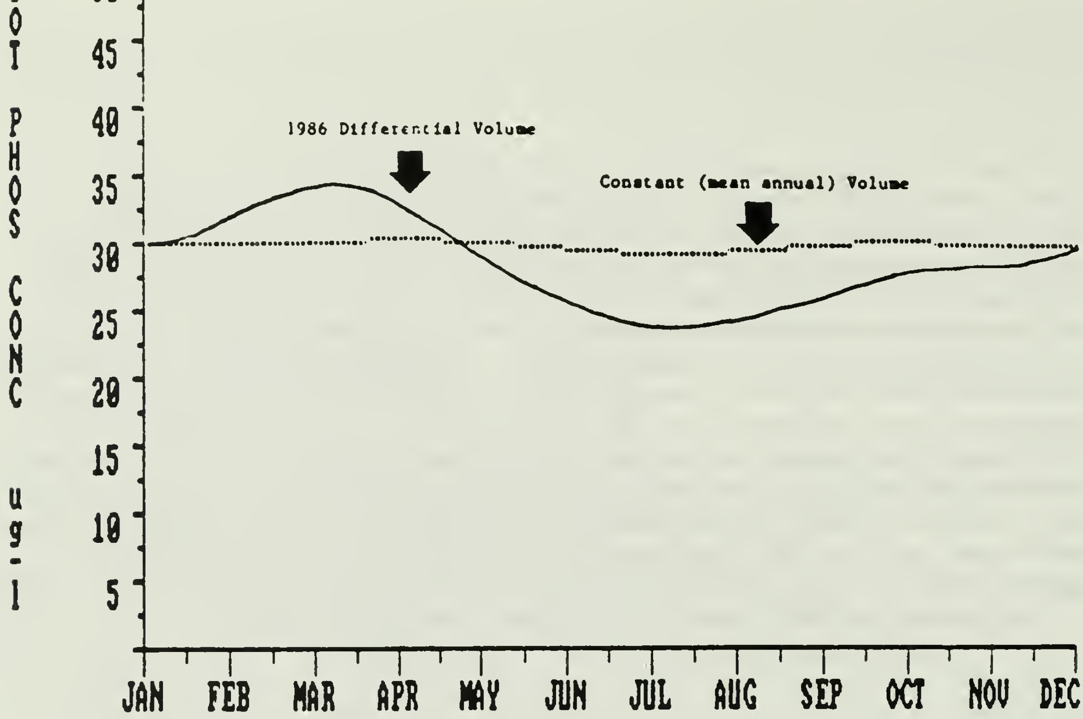


Figure 39. A comparison of model-generated TP concentrations under actual 1986 lake level regime and under constant-volume conditions held at the mean annual lake volume.

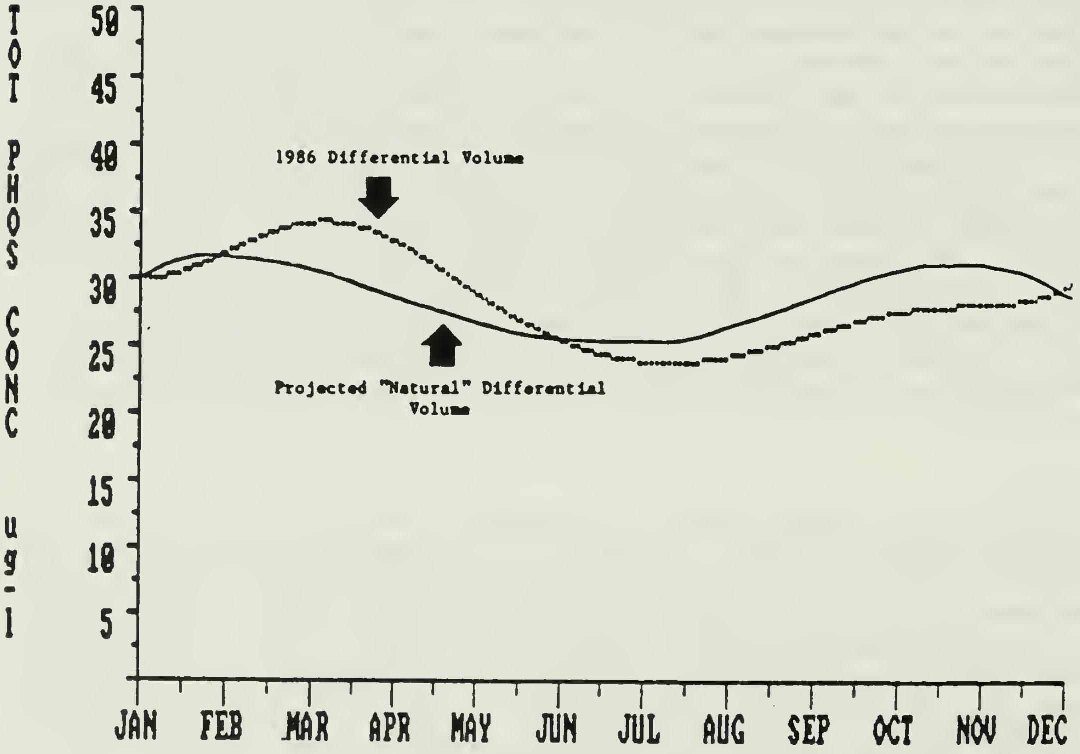


Figure 40. A comparison of model-generated TP concentrations under actual 1986 lake level regime and under projected "natural" (ie., undammed) lake level conditions as presented by Flug (1986).

Perhaps more important is the difference in generated spring TP concentrations around March and April (Fig. 40). At the time when 1986 simulated TP concentration reaches its highest (March 10, at 33.66 $\mu g\ L^{-1}$), concentration under "natural" conditions is somewhat lower (30.16 $\mu g\ L^{-1}$). Although some researchers have found that summer TP is a good predictor of summer chl-a (Prepas and Trew 1983), generally spring TP is the parameter used most often and better fitted to predict summer chl-a concentrations (Dillon and Rigler 1974, Oglesby and Shaffner 1978, Riley and Prepas 1984, Stockner and Shortreed 1984, Ostrofsky and Rigler 1987). Using one of the more frequently cited empirical relationships between spring TP and summer chl-a concentrations (Dillon and Rigler 1974) we obtain a difference in predicted average summer chl-a concentrations between the two model runs. Under 1986 conditions, average chl-a is predicted to be 11.94 mg m^{-3}, while under projected "natural" conditions it is predicted to be 10.18 mg m^{-3}. This translates through another empirical relationship (Dillon and Rigler 1975) to a difference in Secchi disk visibility of 1.6 m under 1986 conditions versus 2.0 m under projected "natural" conditions.

Model-generated TP concentration at ice-out (April 18, 1986) is 30.86 $\mu g\ L^{-1}$. This yields a predicted (Dillon and Rigler 1974) average summer chl-a concentration of 10.36 mg m^{-3}. Combining stations KA and KB, the actual mean summer (May-October) chl-a concentration of Kabetogama Lake during 1986 was 10.54 mg m^{-3}. It appears that TP concentration data collected in spring (around the time of ice-out) would make a good predictor of what mean summer chl-a concentrations will be.

This TP model for Kabetogama Lake is unquestionably an oversimplification of the natural lake system. Nevertheless, the simulation serves its main purpose as a generator of falsifiable hypotheses. Lake drawdown, through its influence on differential volume does effect the TP concentrations in the modeled system. Although the model is uncalibrated and unconfirmed with actual TP data, it is concluded that drawdown can have an effect on nutrient concentrations (eg., TP) in the real Kabetogama Lake just as it does in the modeled system.

Finally it might be pointed out that the model can be used to consider other questions germane to changes in lake trophic conditions. For example, the influence of reducing human TP loadings to zero (as represented by setting the in-basin population to zero, Fig. 41) can be compared with the predicted TP concentration response to a tripling of the in-basin population (Fig. 42). Despite the commonly held view that mathematical models can never adequately describe complex systems like lakes or lake watersheds, these models do provide a means of quantifying, organizing and summarizing information important in making proper lake management decisions.

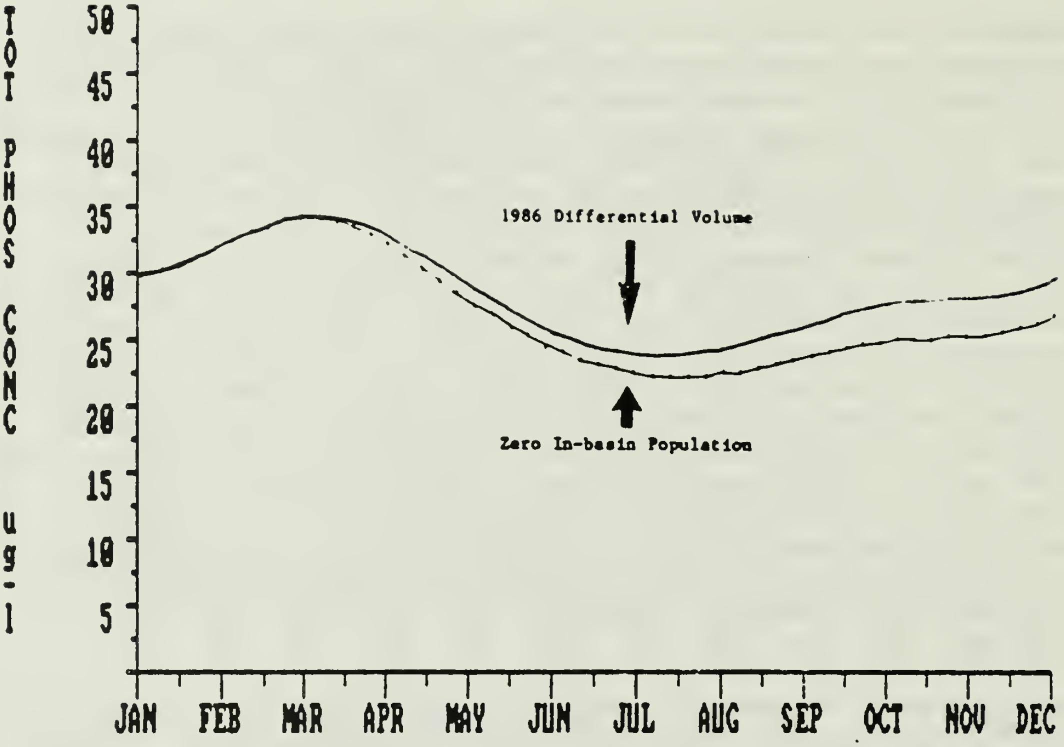


Figure 41. A comparison of model-generated TP concentrations under actual 1986 loading conditions and under zero in-basin population conditions throughout the entire year.

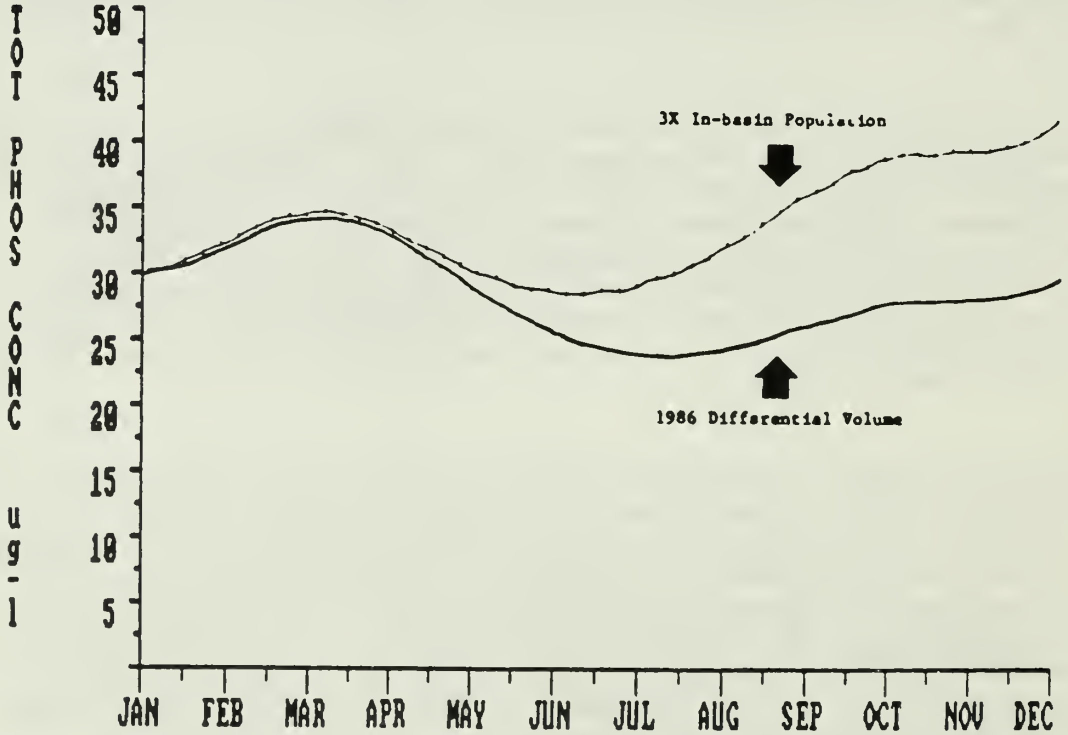


Figure 42. A comparison of model-generated TP concentrations under actual 1986 loading conditions and under conditions of a three-fold increase in the in-basin population size.